ASSESSMENT OF TIME-SERIES MODIS DATA FOR CROPLAND MAPPING IN THE U.S. CENTRAL GREAT PLAINS

by

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ABSTRACT

This study had three general objectives. First, to explore ways of creating and refining a reference data set when reference data set is unobtainable. Second, extend work previously done in Kansas by Wardlow *et al*. (2007) to Nebraska, several exploratory approaches were used to further investigate the potential of MODIS NDVI 250-m data in agricultural-related land cover research other parts of the Great Plains. The objective of this part of the research was to evaluate the applicability of time-series MODIS 250-m NDVI data for crop-type discrimination by spectrally characterizing and discriminating major crop types in Nebraska using the reference data set collected and refined under research performed for the first objective. Third, conduct an initial investigation into whether time-series NDVI response curves for crops over a growing season for one year could be used to classify crops for a different year. In this case, time-series NDVI response curves for 2001 and 2005 were investigated to ascertain whether or not the 2001 data set could be used to classify crops for 2005.

GIS operations, and reference data refinement using clustering and visual assessment of each crop's NDVI cluster profiles in Nebraska, demonstrated that it is possible to devise an alternative reference data set and refinement plan that redresses the unexpected loss of training and validation data. The analysis enabled the identification and removal of crop pattern outliers and sites atypical of crop phenology under consideration, and after editing, a total of 1,288 field sites remained, which were used as a reference data set for classification of Nebraska crop types.

A pixel-level analysis of the time-series MODIS 250-m NDVI for 1,288 field sites representing each of the eight cover types under investigation across Nebraska found that each crop type had a distinctive MODIS 250-m NDVI profile corresponding to the crop

calendar. A visual and statistical comparison of the average NDVI profiles showed that the crop types were separable at different times of the growing season based on their phenology-driven spectral-temporal differences. Winter wheat and alfalfa, winter wheat and summer crops, and alfalfa and summer crops were clearly separable. Specific summer crop types were not easily distinguishable from each other due to their similar crop calendars. Their greatest separability however occurred during the initial spring green up and/or senescence plant growth phases.

In Kansas, an initial investigation revealed that there was near-complete agreement between the winter wheat crop profiles but that there were some minor differences in the crop profiles for alfalfa and summer crops between 2001 and 2005. However, the profiles of summer crops – corn, grain sorghum, and soybeans – displayed a shift to the right by at least 1 composite date, indicative of possible late crop planting and emergence. Alfalfa and summer crops, seem to suggest that time series NDVI response curves for crops over a growing period for one year of valid ground reference data may not be used to map crops for a different year without taking into account the climatic and/or environmental conditions of each year.

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INTRODUCTION

1.1 PROBLEM STATEMENT

Land use/land cover (LULC) data sets at various scales (global, national, regional, or local) are used for scientific, policy, planning, and management applications (Cihlar, 2000; DeFries and Belward, 2000). Such data sets are needed particularly in extensive and dynamic agro-ecosystems such as the Great Plains of the USA. A considerable amount of land in the Great Plains has been converted to intensive agriculture (Gunderson, 1981; Pieper, 2005; Sims, 1988), thus making the region one of the major crop producing areas in the world (Birdsall and Florin, 1998). Accurate and timely information on LULC, particularly on cropland, in the Great Plains region is important because of the direct impact on food security in the USA and the economic impact on world food markets (Doraiswamy *et al*., 2003).

Nebraska and Kansas are two of the major agricultural producing states in the Great Plains. For instance, Nebraska's cash receipts from farm marketing totaled over $12 billion in 2006 (USDA, 2007a), while Kansas' receipts totaled $ 10 billion (USDA, 2007b). However, changes in climate and groundwater availability (USGCRP, 2000; Ojima, 1999) and changing trends in land use management practices and government land use policies (Parton *et al*., 2007) pose serious challenges to the region's long-term agricultural sustainability such as drought mitigation, inadequate irrigation water, soil degradation from current farming systems, and competing land uses. Such a multi-billion-dollar industry therefore needs timely and continuous information regarding crop practices, progress, conditions, and production estimates. As a way of providing 'up-to-date' LULC information and characterizing major human-environmental interactions, monitoring and mapping LULC patterns at regional and global scales on a repetitive basis has been recognized as a necessity (Turner *et al*., 1995; NRC, 2001; NASA, 2002). Remote sensing technology has proven to be a valuable tool for observing, analyzing, characterizing, mapping changes across our ever-changing landscape and environment (Schowengerdt, 1997), because of the higher spatial resolution, a wide range of spectral bands from visible blue through thermal infrared, improved quantization (8-bit), and repeat coverage ability. In recognition of satellite-based sensors' enormous monitoring capabilities, the remote sensing community has been challenged to develop regional to global scale LULC products that characterize 'current' (i.e., periodically updated) LULC patterns, document major LULC changes, and include a stronger land use component (Turner *et al*., 1995; NRC, 2001; NASA, 2002).

Remote sensing technology applications for spectral characterization of crops, early estimation of crop yield and production (Das *et al*., 1993; Domenikiostis *et al*., 2004; Labus *et al*., 2002; Manjunath and Potdar 2002; Shanahan *et al*., 2001; Tucker *et al*., 1980) and cropland mapping at local to regional scales have been studied extensively over the past several decades (Badhwar, 1984; Belward and deHoyos, 1987; Maxwell and Hoffer, 1996; Ortiz, 1997; Wardlow and Egbert, 2008). This information provides timely assessments of conditions, changes in growth, and development of agricultural crops. Such studies have been possible because of the availability of ground reference data sets that are used in combination with remotely sensed data acquired from various sources that include aerial photography and digital imagery from satellite-based sensors such as Landsat Multi-Spectral Scanner (MSS), Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+), and SPOT. However, for many remote sensing based applications, reference date sets are difficult to obtain because they are expensive to collect, inadequate in spatial and temporal coverage, inadvertently inaccurate, outdated, legally restricted, and/or non-existent. Furthermore, the resource and time requirements for the acquisition of reference data for spectral characterization of crops, and cropland classification and mapping over large areas are limited. In addition, most of the studies have been based on single rather than multiple date analysis of the remotely sensed data. This type of analysis may be problematic due to the spectral similarity that different targets may present depending on the calendar date of the single observation (Townshend *et al*., 1987).

Challenges still exist in using parameters derived from remotely sensed data to quantify the changes in crop production (Doraiswamy and Cook, 1995). Even more, there is enormous potential yet to be fully explored in investigating alternative reference data creation and refinement plans, undertaking spectral profile analysis, and carrying out crop classification and mapping using data from new imaging systems, because they have high temporal resolution and moderate spatial resolution. Among the new imaging systems are the Moderate Resolution Imaging Spectroradiometer (MODIS), Medium-spectral Resolution Imaging Spectrometer (MERIS) and Advanced Wide Field Sensor (AWiFS). Both the MODIS and MERIS have enhanced spectral and temporal resolutions, wide geographic coverage, and improved atmospheric corrections. The MODIS offers a unique and greatly improved combination of spectral (36 bands), temporal (daily global coverage), spatial (0.25 to 1 km), and radiometric (12-bits) attributes, compared to previous sensors (Lindsey and Herring, 2002). MODIS' other beneficial attributes include cost-free status and rapid availability of the various data products. MERIS is designed to acquire visible and near infrared radiation in 15 narrow bands (within the 390 – 1040 region of the spectrum) and has a 12-bits radiometric property. MERIS has a dual spatial resolution: reduced spatial resolution (RR) is 1200-m at nadir and full spatial resolution (FR) is 300-m at nadir (Curran and Steele, 2005). AWiFS is one of the cameras on-board the Indian Remote Sensing satellite called Resourcesat-1 (IRS-P6). The sensor has the spatial resolution of 56-m, 4 spectral bands, 10-bit radiometric resolution, and a 24-day temporal resolution (NRSA).

In recent years, the application of MODIS data has become widespread among the LULC research scientists. For instance, the annual production of 1-km global land cover maps used MODIS data (Friedl *et al*., 2002). The data has also been applied in the global land cover classification using decision tree classifiers (Friedl and Brodley, 1997; Hansen *et al*., 2000), in the production of a new land cover map for the Greater Mesoamerica (Giri and Jenkins, 2005), and crop phenology detection (Sakamoto *et al*., 2005). In research conducted at the University of Kansas, Wardlow *et al*. (2007) evaluated the general suitability of time-series MODIS 250-meter EVI and NDVI data for crop-related LULC discrimination in the U.S. Central Great Plains region, and developed and tested a MODIS-based crop mapping protocol (Wardlow and Egbert, 2008). On the basis of this work, it was recommended that further research across the diverse conditions of the U.S. Central Great Plains should be done to build on the Kansas work and to develop a regional crop mapping protocol that could be repeated on an annual basis using the time-series MODIS VI data. It was specifically suggested that areas beyond the Kansas study area should be examined to see whether the methods developed in Kansas would extend to other areas. It was also suggested that the temporal extensibility of time-series signatures be tested, i.e., whether time-series NDVI signatures for one growing season could be used to identify and map crops in another growing season.

In response to these recommendations, time-series MODIS 250-m NDVI data for 2006 were tested in this study for Nebraska to further evaluate their applicability beyond

Kansas. Within Kansas, 2005 MODIS time-series NDVI data were used in the initial investigation into whether time-series NDVI curves for crops over a growing season for one year could be used to map crops for a different year.

1.2 RESEARCH OBJECTIVES

The overall aim of the study was to further investigate, using different exploratory approaches, the potential of MODIS NDVI 250-m data for the spectral characterization, discrimination, and mapping crop types in the Great Plains of the USA. This study had three general objectives:

1) Explore ways of creating and refining a reference data set for various crop-related remote sensing applications, when the reference data set is unobtainable because it is expensive to collect, inadequate in spatial and temporal coverage, inadvertently inaccurate, outdated, legally restricted, or non-existent;

2) Evaluate the applicability of time-series MODIS 250-m NDVI data for crop-type discrimination by spectrally characterizing and discriminating major crop types in Nebraska using the reference data set collected and refined under research performed for the first objective; and

3) Conduct an initial investigation into whether time-series NDVI response curves for crops over a growing season for one year could be used to map crops for a different year. In this case, time- series NDVI response curves for 2001 and 2005 were investigated to ascertain whether or not the 2001 data set could be used to map crops for 2005.

In order to address these three general objectives, this study was divided into three research components and specific research objectives/questions as follows:

Research Component 1: Reference Data Creation and Refinement Strategies

In research component 1, ways for reference data to be generated using GIS operations, and a technique to refine reference data that are non-uniform or "spectrally indistinct using a combination of *k-means* clustering and visual assessment of crops' temporal NDVI cluster profiles, were investigated as essential steps for developing a crop reference data set for Nebraska. In this component, two specific research objectives were addressed.

1. Produce a crop reference data set for Nebraska from the 2006 USDA Crop Data Layer (CDL), and
2. Refine the "noise" crop reference data set using *k-means* clustering and visual assessment of each crop's NDVI cluster profiles.

Research Component 2: Data Exploration: Spectral characterization of major crops using multi-temporal MODIS 250-Meter NDVI data in Nebraska

In research component 2, a combination of graphical and statistical analyses was performed to evaluate the applicability of time-series MODIS 250-m NDVI data for crop type discrimination in Nebraska. Class separability between specific crop types in the time-series MODIS 250-m NDVI was investigated graphically using time-series mean NDVI values along with the periodic-specific ±1 standard deviation of crop-specific NDVI values, and numerically using the Jeffries-Matusita (JM) distance statistic. In this component, two specific research questions were addressed.

1. Do the spectral-temporal profiles of target crops derived from MODIS 250-m NDVI data correspond to their documented crop calendars?

2. Do these spectral-temporal profiles have adequate separablility for crop type identification and subsequently mapping?

Research component 3: **An Inter-Year Comparative Analysis of Phenological Curves for Major Crops in Kansas**

Research component 3 was initiated out of the recognition that reference data sets are often difficult or expensive to regularly collect and therefore may not be available on an annual basis, which is an interval that is desirable to map agricultural land cover (especially crops). Hence the following key research question regarding this work in Kansas was addressed: Are MODIS-based NDVI spectral profiles of major crops (i.e. alfalfa, corn, grain sorghum, soybeans, and winter wheat) different between 2001 and 2005? The assumption was that the MODIS-based NDVI profiles of major crops in Kansas would be relatively stable from year-to-year with minor variations resulting from differences in precipitation and temperature. If this scenario were found to be true, it could be possible to use NDVI response curves for crops over a growing season for one year, created from high quality and complete reference data set, to map crops for a different year without curve adjustments. To address this question, two sets for 2001 and 2005 of MODIS 250-m NDVI spectral profiles were visually compared and statistically evaluated using the Jeffries-Matusita (JM) distance statistic (Richards & Jia, 1999) to determine their degree of similarity.

1.3 BACKGROUND

A large body of remote sensing literature exists on spectral profile analysis, cropland natural vegetation classification, LULC mapping, crop condition assessment, and yield prediction. These various application areas in which remotely sensed data have been used and some of the inherent problems are briefly highlighted below. The characteristics, products, and recent operational research applications of the MODIS sensor are also presented in this section.

1.3.1 Literature Review of LULC Research and Applications by Remote Sensing

Since the inception of the Television and Infrared Observation Satellite (TIROS) in 1960, there has been a continual increase in the availability of improved remotely sensed data at various spatial, spectral, and temporal resolutions, along with advances in computing resources and classification techniques, thus offering the potential to map and monitor LULC at both regional (Eve & Merchant, 1998; Vogelmann *et al*., 2001, Homer *et al*., 2004, Wardlow and Egbert, 2005) and global scales (DeFries and Townshend, 1994; DeFries *et al.,* 1998; Loveland *et al*., 1999; Hansen *et al.,* 2000; Bartholome and Belward, 2005).

Several local- to regional-scale LULC studies undertaken in the USA using remotely sensed data have resulted in information on the collection of ground reference data (Khorram *et al.,* 2001; Lillesand *et al*., 1998; USDA-NASS, 2007; Wardlow and Egbert, 2008), spectral profile analysis (Bauer *et al*., 1980; Daughtry *et al*., 1984; Lo *et al*., 1986; McAdam, 1997; Odenweller and Johnson, 1984; Wardlow *et al*., 2007; Wiegand *et al*., 1990; 1992), cropland and natural vegetation classification (Badhwar, 1984; Belward and deHoyos, 1987; Lauver *et al*., 1999; Maxwell and Hoffer, 1996; Ortiz, 1997; Price *et al*., 1997; Wardlow and Egbert, 2008), LULC mapping (Bartholome and Belward, 2005; Congalton *et al*., 1998; Egbert *et al*., 2001; Ehrlich *et al*., 1994; Maxwell *et al*., 2004; Oetter *et al*., 2001; Whistler *et al*., 1995; Xiao *et al.,* 2006), crop condition assessment (Allen *et al*., 2002; Bauer, 1985; Doraiswamy *et al*., 2004; Wiegand *et al*., 1991), and yield prediction (Das *et al*., 1993; Domenikiostis *et al*., 2004; Labus *et al*., 2002; Manjunath & Potdar 2002; Shanahan *et al*., 2001; Tucker *et al*., 1980).

Many of the studies alluded to above used readily available and up-to-date field site location data and other ancillary information for training and validation. Although Landsat remote sensing technology has been employed in the field of agriculture and has demonstrated that crop types can be discriminated based on their spectral profiles using time-series data (Crist, 1984; Odenweller and Johnson, 1984; Reed *et al*., 1994; Wardlow *et al*., 2007), only a few of these studies have included spectral profile analysis as an initial phase in the overall analysis scheme, particularly as a pre-phase prior to crop mapping. In cropland mapping studies, relatively few have mapped detailed crop-related LULC patterns (e.g., Congalton *et al*., 1998; Ehrlich *et al*., 1994; Maxwell *et al*., 2004; and Maxwell and Hoffer, 1996). Furthermore, most of the cropland maps are infrequently updated, particularly on the time step (e.g. annually) necessary to reflect common LULC changes (e.g. crop rotations) that occur from year to year. Also, most of these studies have generally been limited to a relatively localized scale. In addition, the Landsat and SPOT data that have been used in many of these studies are costly and have low temporal resolution (16 to 26 days, not accounting for off-nadir image acquisitions) thus concealing many details of crop phenology dynamics.

1.3.2 Moderate Resolution Imaging Spectroradiometer (MODIS) Characteristics and Products

MODIS, MERIS and AWIFS are some of the new instruments providing relatively adequate spatial resolution data on a near-daily basis for various operational applications. These new sensors are playing an important role in many global and regional studies since they are filling the information gap between high and low-spatial resolution sensors. In this study, MODIS data were applied to several issues related to crop mapping.

A new era in satellite remote sensing began with the development of the first Earth Observation System (EOS) satellite. The EOS satellite was designed to provide observations that would enable better understanding on a global scale of the entire Earth system and its processes, with considerable attention to enhancing existing databases for climate studies, sea surface temperature, and land cover (Guenther *et al.,* 2002). The first MODIS sensor went into orbit onboard the EOS Terra (EOS-AM1) spacecraft on December 18, 1999 (Lindsey and Herring, 2002). A second MODIS sensor was put into orbit with the successful launch of EOS AQUA (EOS-PM1) spacecraft on May 4, 2002 (NASA, 2007). Wardlow (2005) noted that the design of MODIS was based on the guiding philosophy that the system was to collect a daily coverage of well calibrated multi-spectral, multi-resolution imagery from which a suite of higher-level science quality data sets could be generated to meet the inter-disciplinary needs of the global change research community.

The Terra and Aqua platforms have sun-synchronous, near-polar, circular orbits at 705 km altitude, crossing the equator daily at 10:30 a.m. (Terra) and 1:30 p.m. (Aqua). Terra's morning observations combined with Aqua's afternoon observations provide important insights into the daily biophysical and natural dynamics at global and regional scales. MODIS has 36 spectral bands, 7 of which are designed for the study of vegetation and land surfaces: blue (459-479 nm), green (545-565 nm), red (620-670 nm), near infrared (NIR_1: 841-875 nm, NIR_2: 1230-1250 nm) and short wave infrared ($SWIR_1$: 1628-1652 nm, $SWIR_2$: 2105-2155 nm) (Lindsey and Herring, 2002).

MODIS has several attributes, including daily global coverage, moderate spatial resolution (0.25 to 1km), availability of various products, and cost-free status of data products. Among the products are MODIS 16-day 250/500 m or 1 km Vegetation Index (VI) composite products, comprising NDVI and enhanced vegetation index (EVI) and the 8-day MODIS Surface Reflectance Product at 250 and 500 m spatial resolution. The MODIS VI products are designed to provide consistent spatial and temporal comparisons of global vegetation conditions that can be used to monitor photosynthetic activity, while each 8-day composite provides estimates of surface reflectance of the seven spectral bands mentioned above. The MODIS NDVI serves as a 'continuity index' to the existing AVHRR NDVI record (Lindsey and Herring, 2002). The procedure for generating composited, MODIS-based, VI products is the 'constrained view angle' maximum value compositing method (CV-MVC), in which the highest NDVI value from a series of multitemporal georeferenced images within a specified swath angle range is retained for each pixel location in order to minimize cloud and atmosphere contamination, and standardize sun/view angles (Huete *et al.,* 2002 and 1999; van Leeuwen *et al.,* 1999). MODIS' improved instrumental design contains extensive onboard calibration systems (solar diffuser, solar diffuser stability monitor, and spectro-radiometric calibration assembly) to ensure a calibration accuracy of 2% relative to the sun's radiance (Guenther *et al.,* 2002). In addition, the stable and highly precise external orientation knowledge of MODIS' platform and the availability of accurate global ground control point and digital elevation model data sets allows the MODIS data to have a high level of geolocational accuracy (operational goal of 50-m at nadir and 150-m off-nadir) (Wolfe *et al.,* 2002). The MODIS Land Science Team via the NASA EOS Data Gateway provides a suite of these standard products to users free of charge.

1.3.3 MODIS-based LULC Mapping Research and Applications

Recent regional and national studies have focused more on the applications of MODIS 250-m data, a technology that has the capability of providing information at an intermediate spatial scale between the high spatial resolution and coarse spatial resolution systems, while still providing daily repeat coverage. More literature is becoming available on crop condition and yield prediction (Doraiswamy *et al*., 2004; Muratova *et al*., 2005; Reeves *et al*., 2005; Xu *et al*., 2005) and crop mapping (Doraiswamy *et al*., 2003; Wardlow and Egbert, 2005; Xiao *et al*., 2006; Xavier *et al*., 2006). However, there is limited literature with a focus on spectral analysis for crop mapping (e.g. Wardlow *et al*., 2007), monitoring vegetation dynamics and forage (e.g. Beck *et al*., 2006; Kawamura *et al*., 2005), and mapping rangeland productivity (e.g. Reeves *et al*., 2001). Although a considerable number of research articles on MODIS-based LULC mapping research and applications are beginning to appear in the literature, further work is required to understand crop spectral patterns of MODIS-based NDVI as it relates to climatic variations, management practices and government policies, and as a basis of routine crop identification and mapping over large geographic areas.

1.4 STUDY AREA

This study was conducted in the two states of Nebraska and Kansas, found in the Central Great Plains of the U.S. Several reasons make the states of Nebraska and Kansas ideal study areas for validating the use of MODIS VI data for crop mapping and further testing the applicability of the time-series MODIS data for regional-scale crop characterization and mapping. First, crop production dominates the landscape, providing the most ideal sites for investigation. Second, a number of biophysical and spectral characteristics of crop-related LULC patterns (Wardlow *et al.,* 2007; Wilhelmi & Wilhite, 2002; Yang *et al*., 1997), crop-specific mapping efforts (Wardlow and Egbert, 2008; USDA-NASS, 2007) and vegetation classification and mapping efforts (Egbert *et al*., 2001; Lauver *et al.,* 1999; Whistler *et al*., 1995) have been conducted within Nebraska and Kansas that provide some insight into the key methodological issues for these study sites. Third, a number of data sources (e.g., crop specific profiles/handbooks, crop planting guides, farm facts, and weekly weather and crop bulletins) were available for Nebraska and Kansas to evaluate and validate the results for this research.

Nebraska

The state of Nebraska is situated approximately 40^{o} and 43^{o} N latitude and 95^{o} 25$^{'}$ and 104^{o} W longitude and covers 20 million ha (77,358 square miles) of the U.S. Central Great Plains. Polar and tropical air masses from the north and south respectively, have a great influence on Nebraska. The state has subhumid (in the east) to semiarid (in the west) climatic conditions with precipitation averages more than 760 millimeters (30 inches) annually in the southeast to less than 430 millimeters (17 inches) in the western panhandle. The state's precipitation distribution has a pronounced east-west precipitation gradient. This gradient strongly influences the vegetation types and the cropping patterns and associated management practices. The majority of the precipitation falls during the growing season from April through September. Seasonal temperatures are highly variable with mean low temperatures of – 6^{o} C in January and mean temperatures of 32^{o} C in July.

Extensive grasslands dominate the Nebraska natural vegetation landscape. To the west, sparse rainfall gives rise to short-grass prairie, while increased rainfall in the central part of the states generates mixed-grass prairie. To the east, adequate precipitation occurs to support tall-grass prairie that intermingles with oak-hickory deciduous forest in the far eastern part of the state. Nebraska is among the most intensively cropped states in the U.S. Central Great Plains. Large portions of the state's total area are cropped with alfalfa (*Medicago sativa*), corn (*Zea mays*), sorghum (*Sorghum bicolor*), soybeans (*Glycine max*), and winter wheat (*Triticum aestivum*). Alfalfa (USDA, 2000a), corn (USDA, 2006), sunflowers (Thomas *et al*., 2003), and winter wheat (Hein and Kamble, 2003) are grown across the entire state of Nebraska. Although corn, sunflowers, and winter wheat are found throughout the state, corn is predominantly grown in the eastern third and southern half of the state mostly grown under irrigation using water from the Ogallala aquifer and large surface irrigation impoundments, sunflowers are greatly concentrated in the lower rainfall areas of western Nebraska, while 75% of winter wheat production is in the western half of the state were it is grown in a wheat-fallow rotation with the fallow period used to increase water storage in the soil. Sorghum (USDA, 2000b) is grown primarily in the southern counties of the state were it is planted as a non-irrigated crop because it is a drought resistant crop, while soybeans (USDA, 2000c) are primarily produced in the eastern half of Nebraska with highest production in the eastern third of the state and about one third of the state's soybeans acres are irrigated.

Kansas

Kansas is situated approximately 37^{o} and 40^{o} N latitude and 94^{o} $38^{'}$ and 102^{o} 94° 1' W longitude and covers an area of 21,310,940 ha (82,282 square miles) of the U.S. Central Great Plains. The state has a mid-continental temperate climate with a pronounced east-west precipitation gradient. This gradient strongly influences the vegetation types, the cropping patterns and associated management practices. On average, western Kansas receives 460-510 millimeters (mm) of precipitation per year, central Kansas receives 900 mm, and eastern Kansas receives 890-1020 mm. Seasonal temperatures are highly variable with mean low temperatures of – 6^{o} C in January and mean high temperatures of 32^{o} C in July. The majority of the precipitation falls during the growing season from April through September.

Extensive grasslands dominate the Kansas natural vegetation landscape. To the west, sparse rainfall gives rise to short-grass prairie, while increased rainfall in the central part of the state generates mixed-grass prairie. To the east, adequate precipitation occurs to support tall-grass prairie that intermingles with oak-hickory deciduous forest in the far eastern part of the state. A larger portion of the state's total area is intensively cropped with alfalfa (*Medicago sativa*), corn (*Zea mays*), sorghum (*Sorghum bicolor*), soybeans (*Glycine max*), and winter wheat (*Triticum aestivum*). Eastern Kansas generally receives adequate precipitation to support mainly corn and soybeans production without irrigation, and fallow is non-existent. In semi-arid western Kansa, alfalfa, corn, and soybeans are grown under irrigation because of limited precipitation. High crop production levels are maintained due to extensive irrigation from primarily groundwater sources and dryland farming techniques (e.g., crop-fallow rotations and non-till farming). The non-irrigated areas of western Kansas are planted to dryland crops such as sorghum or winter wheat or remain fallow to conserve soil moisture for crop production the next year. The variability in the NDVI signals for a specific crop exhibited across the state is a confirmation of regional variations in climate and management practices (Wardlow *et al*., 2006). It has further been noted that Kansas also contains large acreages of former cropland that are now covered with native and non-native grasses as part of the USDA Conservation Reserve Program (CRP) (Egbert *et al.,* 1998).

1.5 DATA

1.5.1 MODIS 250-m NDVI and Other Data Sets

In research component 1 and 2, three data sets were used in creating and refining a crop reference data set for Nebraska. The data sets include the following: (i) 16-day composite MODIS 250-m NDVI data (MOD13Q1 Collection 004) spanning from January 1 to December 3, 2006 acquired from the NASA EOS Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/); (ii) 56m 2006 Nebraska Crop Data Layer (CDL), derived from AWiFS satellite data and produced by USDA-NASS (USDA-NASS, 2007); and (iii) Kansas state average NDVI profiles from 2001 MODIS data for the five major crops of alfalfa, corn, grain sorghum, soybeans, and winter wheat (Wardlow et al., 2007).

In research component 3, the following data sets were used: (i) the 16-day composite MODIS 250-m NDVI data (MOD13Q1 Collection 004) spanning from January 01 to December 19, 2005 acquired from the NASA EOS Data Gateway, (ii) a 2005 Kansas Common Land Unit (CLU) data layer, polygons that are based on crop type grown as reported by farmers, from the USDA Farm Service Agency (FSA), and (iii) Kansas state average NDVI profiles from 2001 MODIS data (Wardlow, et al., 2007) for the five major crops of alfalfa, corn, grain sorghum, soybeans, and winter wheat.

1.5.2 Field Site Database

Research components 1 and 2 used the field sites created and refined using GIS operations, clustering, and visual evaluation of cluster profiles. A field site data set for specific crop types was created using the 56-m 2006 Nebraska CDL, produced by USDA-NASS (USDA-NASS, 2007). The 56-m 2006 CDL was derived from ground-based data for crops growing within the state at the time of the June survey, using IRS AWiFS imagery and Common Land Unit (CLU) as a source of training and validation data.

The seven crops and fallow land cover type raster layers were separated from the CDL by creating new raster files using a raster calculator in Spatial Analyst, a GIS extension tool. Each separate layer was converted from raster into polygon layer using a GIS raster to polygon conversion tool. Subsequently, the size of each polygon was calculated using pre-logic Visual Basic for Applications (VBA) script code. This was necessary to reduce the number of polygons for each crop layer to a manageable size. Therefore, the average size of the smallest contiguous polygon for the most predominant crops (alfalfa, corn, soybeans, and winter wheat) was set at 56.25 ha (approximately 9 MODIS 250-m pixels), and 37.5ha (approximately 6 MODIS 250-m pixels) for the less predominant crops for which smaller acreages were planted (grain millet, sorghum, and sunflower) and fallow.

A three-composite-date MODIS NDVI raster in which the crop was expected to have attained considerable growth and maturation was created for each cover type and was used as a background to the crop polygon layers. Each crop's polygons that overlapped with the MODIS NDVI raster for the three composite dates were selected. The selected polygons corresponded to the polygon size of above 500 ha for corn and soybeans; above 100 ha for grain millet and winter wheat; above 45 ha, 40 ha, and 30 ha for alfalfa, sorghum, and sunflower, respectively. The three-composite-date MODIS NDVI raster was also created and used as a background for the fallow polygon layer. The fallow polygons that overlapped with the low MODIS NDVI values were selected. The polygon size of these selected was greater than 85 ha.

The centroids for each polygon used in the analysis was computed and examined to determine whether its computed location as accurate. The accuracy was assessed by looking at the geographic location of each centroid to determine whether it appeared near the center of each polygon. Centroids that fell just outside or inside the polygon boundaries were manually shifted to the middle of the polygon to ensure that the NDVI values extracted at the centroid locations were away from the polygon edges which would result in the use of NDVI values from mixed pixel cover types. Centroids that fell too far outside the contiguous polygons were removed from the database. The MODIS NDVI grid for the three composite dates for each of the eight crop and fallow layers were used as a background to aid in the selection of a suitable single 250-m pixel to represent each field site. The geographic locations of 1,576 initial centroids that meet the locational criteria as demonstrated above were then considered as the locations of each crop's initial field sites.

A total of 1,576 field sites representing the eight cover types under investigation were used as a basis for extracting time-series NDVI values. To refine the reference data set, the extracted NDVI data from the ' initial field sites' for each crop type (excluding fallow) were subjected to cluster analysis (Romesburg, 2004), using *k-means* clustering, as a way of evaluating variability among field sites within each crop type.

Several cluster sizes were tried and in each case profiles were plotted and visually examined. Since some larger cluster sizes did not have members, the maximum cluster size of 10 was assumed adequate. Three cluster data sets of 10, 7 and 3 clusters were generated for crops with a large number of field sites (e.g. alfalfa, corn, soybeans, and winter wheat), while for crops with a relatively small number of field sites (e.g. millet, sorghum, and sunflowers) two data sets of 5 and 3 clusters were generated.

After clustering, each cluster's NDVI profiles for each specific crop was created and visually compared to the known MODIS-based profiles of similar crops in Kansas. Due to the fact that data sets with fewer clusters tended to conceal subtle differences among field sites, the 10-cluster data set for crops with large number of field sites and 5-cluster data set for crop with a relatively small number of field sites were deemed adequate in revealing the field sites' variability. Cluster profiles that were consistent with the spectral-temporal profiles of a similar crop in Kansas were aggregated to represent crop-specific, state-level time-series NDVI profiles for Nebraska. Using this refining process, cluster profiles that were outliers for sites atypical of Kansas's crop phenology were identified and removed. Profiles of millet and sunflower were not available for Kansas. Millet cluster profiles were evaluated independently and a profile that was consistent with the general seasonal pattern of an annual crop growth cycle was selected. A typical sunflower profile was selected after sunflower cluster profiles were compared to the Landsat-based profiles demonstrated in Odenweller & Johnson (1984). After completing this field site refinement process, there were 1,288 sites retained for further analysis.

In research component 3, Common Land Units (CLUs), from the USDA Farm Service Agency (FSA) were as a basis for creating field sites. Due to limited time, only non-irrigated fields were considered for this study. Separate databases for the five major crops were created by selecting non-irrigated fields larger than 32.4 ha (80 acres approximately five 250-m MODIS pixels) from the CLU data layer using GIS operations. Point-labeling all CLUs created center points for each crop polygons. The total number of initial samples for 2005 was 1,615. This sample size, representing all the five crop types under investigation was used as a basis for extracting time-series NDVI values. The extracted NDVI data from the initial field sites for each crop type were subjected to cluster analysis (Romesburg, 2004), using *k-means* clustering, as a way of evaluating variability among field sites within each crop type, and to identify and eliminate outliers. The 2005 NDVI cluster profiles were visually compared to the 2001 MODIS-based profiles for the same crops in Kansas, derived from earlier work by Wardlow (Wardlow, et al., 2007). Each crop's NDVI cluster profiles that were consistent with the spectral-temporal profiles of the same crop in Kansas were aggregated to represent crop-specific, state-level multi-temporal NDVI profiles. Outliers and sites atypical of Kansas's crop phenology (361 in total) were identified and removed. The final field sites, totaling 1,254 whose average NDVI profiles appeared to be consistent with the known crop profiles, constituted the crop reference data set for Kansas in 2005.

1.6 DISSERTATION OVERVIEW

There are five chapters in this dissertation. This introductory chapter includes the problem statement, research objectives, literature review, study area description, research data, and the dissertation outline. In chapter 2, agricultural field site creation for the Nebraska dataset and refinement strategies for the extracted spectral curves is analyzed. Spectral profile characterization and discrimination using visual and statistical comparisons of the average NDVI profiles of major crops in Nebraska are discussed in chapter 3. Comparison of MODIS time-series NDVI profiles for 2001 and 2005 in Kansas is presented in chapter 4. Chapter 5 summarizes this research by highlighting the major findings and conclusions from previous chapters and suggestions for future studies are also presented.

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Chapter 2

AGRICULTURAL GROUND REFERENCE DATA SET CREATION AND REFINEMENT

CHAPTER SUMMARY

Quality reference data are of critical importance for most remote sensing-based research activities. Data quality factors often include precision, representativeness, validity and timeliness. However, several problems such as lack of funds for data collection, the data's limited spatial and temporal validity, and unavailability would compromise the data quality.

The aim of this research was to explore ways of creating and refining a reference data set for various remote sensing applications (e.g., crop characterization, land use/land cover (LULC) mapping and monitoring, crop condition assessment and yield prediction), when the reference data set is unobtainable because it is expensive to collect, inadequate in spatial and temporal coverage, inadvertently inaccurate, outdated, legally restricted, or non-existent. The objectives of the research were to (i) to produce a crop reference data set for Nebraska from the 2006 U.S. Department of Agricultural (USDA) Crop Data Layer (CDL), and (ii) to refine the crop reference data set using *k-means* clustering and visual assessment of each crop's normalized difference vegetation index (NDVI) cluster profiles.

The 16-day composite time-series MODIS 250-m NDVI data (MOD13Q1 Collection 004) spanning from January 1 to December 3, 2006 were used. CDL digital crop layers were converted into polygons, using GIS raster to polygon conversion tool, and the geographic

location of the centroid of each polygon was linked to each crop's field sites. A total of 1,576 field sites representing all the crops under investigation were selected and used as a basis for extracting time-series NDVI values. An average value from a single pixel within the polygon was used to represent each field's NDVI value.

Time-series of NDVI values was input into the clustering analysis and a *k-means* clustering analysis was performed on the time-series NDVI values to compute similarity indices for all the field sites. After clustering, profiles from multiple clusters per crop type were visually compared to the known MODIS-based profiles of the same crops types in Kansas. The crop types for Nebraska were then determined by matching crop NDVI cluster profiles for Nebraska to those of known crop NDVI phenological pattern of Kansas. Nebraska and Kansas's general NDVI profiles were expected to be similar because in both states the topographic conditions, precipitation pattern, and the management practices are generally similar. Crop pattern outliers and sites atypical of crop phenology under consideration were identified and removed. After editing, a total of 1,288 field sites remained which were used as a reference data set for classification of Nebraska crop types.

2.1 INTRODUCTION

The Great Plains region of the U.S.A. is one of the major crop producing areas in the world (Birdsall & Florin, 1998). Changes in climate and ground water availability (USGCRP, 2000; Ojima, 1999), however, and changing trends in land use management practices and government land use policies (Parton *et al*., 2007) pose serious challenges to the region's agro-ecosystems such as drought mitigation, soil degradation, and competing land uses. These challenges create a demand for crop related information on a regular basis, and remote sensing technology can be utilized for rapid collection and update of crop information.

Agricultural data, of which ground data sets are key, are comprised of many data types such as crop types, acreage, plant and harvest dates, soil types, and management practices. Ground reference data are of significant value to most remote sensing-based research activities. These data are collected among other reasons for (i) calibration and validation of remote sensing imagery and its data products, (ii) feasibility studies for airborne/spaceborne missions and (iii) basic investigation of the relationship between physical or biochemical properties and the electro-magnetic reflectance of objects (Hüni *et al*., 2007). Lillesand *et al*. (1998) however pointed out that most reference data sets are collected for purposes of training the computer algorithms to recognize the various land cover categories latent in the satellite imagery and assessing the categorical accuracy of the resulting classification.

High quality reference data are often characterized by their precise, representative, valid, and timely nature (Mussa, 1996). Quality reference data are an integral component of most remote sensing-based research projects and have been invaluable for a variety of applications including LULC classification. How often a data update is required depends on the nature of the features of interest. According to Bronsveld *et al*. (1994) some features do not change within the time-span of a study's objectives (e.g. soil parent material) and hence they do not have to be surveyed more than once. Other features, particularly in agro-ecosystems, change rapidly, thus justifying regular updates of reference data. For instance, Lillesand *et al.* (1998) attest that crop types often change annually because of crop rotation and the collection date of agricultural ground reference data must match the satellite imagery as closely as possible.

Although reference data are vital in remote sensing-based research projects, in many cases and for various reasons, the data are of poor quality. There are several problems that impact the availability of high quality reference data. First, the collection of reference data is an expensive process and adequate financial resources are often lacking to support this activity (Bronsveld *et al*., 1994). This problem is particularly common in the third world countries with inadequate resources at their disposal. Second, reference data sets, especially those related to plant phenomena that change over time, are often few in number and limited in their spatial and temporal validity (Bronsveld et al., 1994). Lillesand *et al*. (1998) acknowledged this constraint, by pointing out that ground reference data generally cannot be collected for large portions of an entire project area, or even for multiple time periods. Finally, in some instances the reference data are inadvertently inaccurate, outdated, unobtainable due to legal restrictions including inaccessibility to land parcels, or non-existent.

Dynamic agro-ecosystems, such as those found in the U.S. Great Plains, create a demand for collecting crop-related reference information on a regular basis, and the need to ameliorate problems that impact on the quality of reference data. As a result, more focused research on compensating for a lack of up-to-date, high quality reference data in this type of region is needed.

2.1.1 Reference Data for Remote Sensing Applications

Since the inception of the Television and Infrared Observation Satellite (TIROS) in 1960 (Landgrebe, 1997), satellite-based remote sensing has offered unrivalled capabilities for monitoring, forecasting, managing, understanding and decision making about the earth's resources (Schowengerdt, 1977; Zhou and Baysal, 2004). The need for a better understanding and management of earth resources among many reasons provided the impetus for the development of this technology (Landgrebe, 1997; Zhou and Baysal, 2004). Satellite-based sensors such as Landsat's Multi-Spectral Scanner (MSS), Thematic Mapper/Enhanced

Thematic Mapper Plus (TM/ETM+), the Advanced Very High Resolution Radiometer (AVHRR), and the more recent Moderate Resolution Imaging Spectroradiometer (MODIS) have been employed in many earth resources studies both in the U.S.A. and throughout the world.

Many earth resources studies have, among many topics, focused on spectral profile analysis (Bauer *et al*., 1980; Daughtry *et al*., 1984; Lo *et al*., 1986; McAdam, 1997; Odenweller and Johnson, 1984; Wardlow *et al*., 2007; Wiegand *et al*., 1990; 1992), cropland and natural vegetation classification (Badhwar, 1984; Belward & deHoyos, 1987; Lauver *et al*., 1999; Maxwell *et al*., 2004; Ortiz, 1997; Price *et al*., 1997; Wardlow and Egbert 2008), LULC mapping (Bartholome & Belward, 2005; Congalton *et al*., 1998; Egbert *et al*., 2000; Ehrlich *et al*., 1994; Maxwell and Hoffer, 1996; Oetter *et al*., 2001; Whistler *et al*., 1995; Xiao *et al*., 2006), crop condition assessment (Allen *et al*., 2002; Buer, 1985; Doraiswamy *et al*., 2004; Wiegand *et al*., 1991), and yield prediction (Das *et al*., 1993; Domenikiostis *et al*., 2004; Labus *et al*., 2002; Manjunath and Potdar 2002; Shanahan *et al*., 2001; Tucker *et al*., 1980). The above-cited studies demonstrate how remote sensing technology has the potential for diverse applications (Landgrebe, 1997) and have provided essential tools and data for generating the needed information. In all these studies, quality reference data were an invaluable input, which illustrates the importance for this type of information for remote sensing-based research projects that require ground truthing and validation of the classification output results.

In recent years, the application of MODIS data has become widespread among LULC research scientists. For instance, the annual production of 1-km global land cover maps used MODIS data (Friedl *et al*., 2002). The data has also been applied in the global land cover classification using decision tree classifiers (Friedl and Brodley, 1997; Hansen *et al*., 2000), in the production of a new land cover map for the Greater Mesoamerica (Giri and Jenkins, 2005), and crop phenology detection (Sakamoto et al., 2005). More literature is becoming available on crop condition and yield prediction (Doraiswamy *et al*., 2004; Muratova *et al*., 2005; Reeves *et al*., 2005; Xu *et al*., 2005) and crop classification and mapping (Doraiswamy *et al*., 2003; Wardlow and Egbert, 2008; Xiao *et al*., 2006; Xavier *et al*., 2006). The MODIS Land Science Team provides a suite of standard MODIS data products to users that include the 16-day NDVI and enhanced vegetation index (EVI) composites. The MODIS NDVI serves as a 'continuity index' to the existing AVHRR NDVI record (Lindsey and Herring, 2002). EVI was designed to minimize the effects of the atmosphere (e.g., aerosols) and canopy background (e.g., soil and plant litter) that contaminate the NDVI (Huete *et al*., 1997) and enhance the green vegetation signal (Huete *et al*., 2002). The procedure for generating composited, MODIS-based, Vegetation Index (VI) products is the 'constrained view angle' maximum value compositing (CV-MVC), in which the highest NDVI value from a series of multitemporal georeferenced images within a specified swath angle range is retained for each pixel location in order to minimize cloud and atmosphere contamination and standardize sun/view angles (Huete *et al.,* 2002 & 1999; van Leeuwen *et al.,* 1999). The MODIS is an improved instrument due to its better design (e.g., solar diffuser, solar diffuser stability monitor, spectro-radiometric assembly, and high level of geolocational accuracy) (Guenther *et al*., 2002; Wolfe *et al*., 2002). The MODIS offers a unique and greatly improved combination of spectral (36 bands), temporal (daily global coverage), spatial (0.25 to 1 km), and radiometric (12-bits) attributes, compared to previous sensors (Lindsey and Herring, 2002). MODIS' other beneficial attributes include cost-free status and rapid availability of the various data products.

2.1.2 Examples of Ground Reference Data Collection Methods

Hüni *et al*. (2007) and Lillesand *et al.* (1998) discuss the applications of ground reference data. They explain that different ground reference data collection methods are employed depending on the data collection purpose, the availability of primary sources of reference data, and the adequacy of interpretation and field staff. Although the collection methods of reference data may vary, the collection process is usually accomplished in several basic steps such as choosing the primary source of reference data, pre-selection of field sites, interpretation of features in remotely sensed images, and field visits or sampling.

The primary source of reference data is either remotely sensed products such as aerial photographs, satellite imagery, and thematic maps, or field visits (Wickham *et al*., 2004; Kauneckis *et al*., 1998). Pre-selection of field sites are done by image interpretation as a way of minimizing staff time in the field and ensuring that useful ground sites are captured (Lillesand *et al*., 1998). During the visual interpretation phase, interpreters precisely locate each site on the remotely sensed product. Interpreters then examine the area around the site using conventional photo-interpretation keys (e.g., tone, color, shape, pattern, and texture) and determine the LULC class label for each site according to the selected classification scheme. During field visits and/or sampling, field crews navigate to pre-selected reference sites using a Global Position System (GPS). At each site, the actual coordinates and time, physical parameters (e.g., slope, aspect, elevation, and land form), and biophysical measurements (e.g., ecological system type, general vegetation cover type, and/or inventory of crop types) are recorded. Three research projects are presented here to illustrate the variety of source materials and steps employed in the collection of ground reference data.

(i) USDA-National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) Program

The USDA-NASS has produced high resolution Cropland Data Layers (CDLs) since 1997 for several states in the U.S. to enhance their crop acreage estimates. As of 2006, CDLs were published annually for ten states, which included Nebraska. The CDL is a raster, categorized land cover data layer of specific crop types produced using satellite imagery. Crop type classification is completed by using statistically sampled field data on planted crops collected each June (Allen *et al*., 2002). Although the CDL program is being implemented in many states, an example of the 2006 CDL for Nebraska will be used to illustrate the program's reference data collection process.

USDA-NASS began annual CDL production for Nebraska in 2001 using 30-m Landsat TM/ETM+ imagery. A multi-date approach was employed and typically a spring and summer observation date of observation was preferred for maximum crop separation. In 2006, Nebraska's CDL was produced, however, using a total number of 13 satellite scenes to cover Nebraska from the Indian Remote Sensing (IRS) Resourcesat-1 Advanced Wide Field Sensor (AWiFS) that has a ground resolution of 56-m. The images were collected between the dates of May 19, and August 03, 2006. Field data on planted crops come from the annual NASS June Area Survey (JAS) and/or the annual Farm Service Agency's (FSA) Common Land Unit (CLU) data. The data collection process is a county-level, field-based survey detailing the exact location (fields' latitude and longitude corner points), acreage, crop type, and owner of sampling sites. After the field survey, the sample crop fields were manually digitized by the USDA-NASS over single date AWiFS image mosaic and assigned a crop type attribute based on what the farmer planted in 2006. The AWiFS image mosaics were then sampled and used as training inputs during the CDL classification. The map classification accuracy was generally between 85% and 95% correct for the crop type categories (USDA-NASS, 2007).

(ii) The Center for Earth Observation (CEO) Region 5 Dataset Accuracy Assessment Project

The Center for Earth Observation (CEO) at North Carolina State University carried out a project to evaluate and analyze the accuracy of the Federal Region 5 (Midwest states) dataset of the Multi-Resolution Land Characteristics (MRLC) National Land Cover Data (NLCD) (Khorram *et al*., 2001). The NLCD program provided a consistent and conterminous land cover map of the lower 48 States at approximately an Anderson Level II thematic detail (Khorram *et al*., 2001; Wickham *et al*., 2004).

The data used for the project were: the geographic locations of 1,800 reference sites in a digital file of X, Y map coordinates; National Aerial Photography Program (NAPP) photos containing these reference sites; and the false color composite (FCC) Landsat Thematic Mapper (TM) image data (bands 3, 4, and 5) for the area surrounding each reference site. Khorram *et al*., (2001) pointed out that since there is no suitable existing ground reference data set that can be used for all federal regions, a practical and statistically sound sampling plan was needed to characterize the accuracy of both the common and rare classes in the NLCD. Therefore, a stratified random sampling design was used to select 1,800 sample sites – 100 for each of the 18 classes present in Region 5. This was done in several steps: First, the region was divided into 60 km by 30 km frames. Second, each frame was further subdivided into 50 primary sampling units (PSU). Third, one PSU was selected at random from each frame. Finally, the 1,800 sample sites were selected by stratifying based on NLCD land cover class within the selected set of PSUs. The PSUs were randomly assigned to photo interpreters. The selected reference site locations were plotted on the Landsat TM image chips, and the photo interpreters precisely located each site on the image and subsequently located the reference sites on the corresponding photo, on the basis of the spatial and spectral context provided by the FCC Landsat TM image. Interpreters then examined a 3 by 3 TM pixel window around the site on the aerial photo and determined the LULC class label according to the NLCD classification scheme for each sample site based on visual interpretation cues. Only 1,643 of the initial 1,800 randomly selected points were completed. The other sites were not included because of incorrect photos supplied and missing or unavailable photos and image data for parts of the study area. Therefore, the data collection process culminated in the production of a reference database comprised of thematic information for 1,643 sample sites that could be used for accuracy assessment.

(iii) The MODIS 250-m Vegetation Index (VI) Data Application in Kansas

In research conducted by Wardlow *et al*. (2007), they evaluated the general suitability of time-series MODIS 250-meter EVI and NDVI data for crop-related LULC discrimination in the U.S. Central Great Plains region (Wardlow *et al*., 2007), and developed and tested a MODIS-based crop mapping protocol (Wardlow and Egbert, 2008).

The data comprised: a 12-month time-series of 16-day composite MODIS 250-m EVI and NDVI data; annotated aerial photos from the USDA Farm Service Agency (FSA) for ~2,800 individual fields in Kansas that were 32.4 ha (80 acres) or larger, containing the field's geographic location, crop type in 2001, acreage, and irrigation/non-irrigation designation; a georeferenced Public Land Survey System (PLSS) coverage; and Landsat ETM+ imagery. A field database comprising field site locations, crop types, management practices, and time-series EVI and NDVI data for each crop type was created using information from annotated aerial photos. The process involved locating 2,800 field sites on the MODIS imagery using a georeferenced PLSS coverage and Landsat ETM+ imagery and selecting a single 250-m pixel located completely within the field's boundary to represent each field. Time-series VI data were then extracted for the pixel and visually evaluated to verify that their spectral-temporal characteristics were consistent with the crop type reported by the FSA. After verification, the field's time-series VI data and annotated crop information were entered into the database. This process was repeated for each of the ~2,800 field sites and a total of 2,179 field sites were retained. The other sites were not included because their spectral temporal characteristics were not consistent with the crop type reported by the FSA.

The above-cited examples used readily available and up-to-date field site location data and other ancillary information for CDL classification (USDA-NASS, 2007), accuracy assessment (Khorram *et al*., 2001), and crop classification (Wardlow *et al*., 2007). In the event that no suitable existing ground reference data are available for use in any LULC related research, it would be imperative to devise an alternative reference data creation and refinement plan.

2.1.3 Research Objectives

This research was initiated in response to the demand for crop-related information on a regular basis and the need to ameliorate problems that arise when adequate reference data are not available. In particular, the unexpected loss of access to training and validation data from USDA FSA made this topic invaluable. The overall goal of this research was to explore robust ways of creating and refining a reference data set for remote sensing-based research work when the reference data set are too expensive to collect, inadequate in spatial and temporal coverage, inaccurate, outdated, legally restricted, or non-existent. Strategies for reference data generation using GIS software, and reference data refinement using *k-means* clustering and visual assessment of crops specific time-series NDVI data, were investigated as essential steps for developing a crop reference data set for the state of Nebraska. The objectives of the research were: (i) to produce a crop reference data set for Nebraska from the 2006 Crop Data Layer (CDL), and (ii) to refine the crop reference data set using *k-means* clustering and visual assessment of each crop's multi-temporal NDVI cluster profiles.

Overall, the research will contribute to the existing body of knowledge on ground reference data collection protocols. This research will be especially useful in regions were reference data sets are often not available. For instance, Zambia, the researcher's home country, is endowed with enormous non-renewable and renewable resources. The unprecedented utilization of both forestry and agricultural resources in the recent past has created a need for up-to-date maps for resource planning and management purposes. The characterization and mapping of such dynamic resources however have been hampered by the inadequacy of reference data sets at a national level. Therefore, apart from redressing the unexpected loss of access to training and validation data in the U.S., this research will be essential for future work in the forestry and agricultural sectors of many countries such as Zambia.

2.2 STUDY AREA

This study was conducted in the state of Nebraska (Fig. 2.1), which is situated in the heart of the central Great Plains region of North America. The agricultural sector of Nebraska is intensively developed with approximately 93% of the state's total area (18.4 million ha/45.7 million acres) under cropland and ranches (Nebraska Department of Agriculture, 2007).

Figure 2.1 The State of Nebraska study area map

The agricultural landscape consists of a mosaic of relatively large fields, where the average farm size is about 388 ha /980 acres with diverse crop types and management practices (USDA, 2007). The major crops grown in Nebraska include: alfalfa (*Medicago sativa*), corn (*Zea mays*), (proso) millet (*Panicum miliaceum L*), sorghum (*Sorghum bicolor*), soybeans (*Glycine max*), sunflowers (*Helianthus annuus*), and winter wheat (*Triticum aestivum*) (USDA, 2007). Alfalfa (USDA, 2000a), corn (USDA, 2006), sunflowers (Thomas *et al*., 2003), and winter wheat (Hein and Kamble, 2003) are grown across the entire state of Nebraska. Although corn, sunflowers, and winter wheat are grown throughout the state, corn is predominantly grown in the eastern third and southern half of the state (USDA, 2006), sunflowers are greatly concentrated in western Nebraska (Thomas *et al*., 2003), soybeans are predominant in the eastern half of Nebraska (USDA, 2000c), while 75% of winter wheat production is in the western half of the state (Hein and Kamble, 2003). Millet production is mainly concentrated in the wheat growing areas of the western half of Nebraska where it is grown in a wheat-millet rotation (Hein and Kamble, 2003), while sorghum is grown primarily in the southern counties of the state (USDA, 2000b).

Nebraska has a dry, mid-continental climate characterized by cold winters and hot summers, and the average annual temperature ranges from 11^{o} C (52^{o} F) in the southeast to about 9^{o} C (48^{o} F) in the extreme northwest (Britannica Student Encyclopedia, 2007). Variations in the growing season range from 165 days annually in the southwest to 125 days annually in the northwest. The state's total precipitation varies considerably from year to year and averages more than 760 millimeters (30 inches) annually in the southeast to less than 430 millimeters (17 inches) in the western panhandle, and the greatest amounts of the precipitation falls as rain during the growing season between the months of April and September (Britannica Student Encyclopedia, 2007). Nebraska, therefore, has pronounced climatic gradients: a north-to-south elevation in temperature, an east-to-west decrease in mean precipitation, and an east-to-west increase in evapotranspiration, all of which mainly determine the state's environmental and land use characteristics (Wilhelmi and Wilhite, 2002).

2.3 DATA AND METHODS

A 12-month time-series of 16-day composite MODIS 250-m NDVI data for field sites of eight crop cover types – alfalfa, corn, millet, sorghum, soybeans, sunflowers, winter wheat, and fallow - were analyzed across Nebraska. A total of 1,576 field sites representing each of the eight cover types under investigation were created from the 2006 Cropland Data Layer (CDL) for Nebraska, from the USDA-National Agriculture Statistics Services (USDA-NASS). The geographic locations of these field sites were used as a basis for extracting time-series NDVI values. After refining the data set using a *k-means* clustering analysis and visually evaluating each crop's cluster mean profile to verify that their respective spectral-temporal profiles were consistent with the known MODIS-based profiles of similar crops in

Kansas, a total of 1,288 field sites were retained for analysis. A brief discussion of the data and methods used is provided below.

2.3.1 Time-Series MODIS NDVI Data

The 16-day composite MODIS 250-m NDVI data (MOD13Q1 Collection 004) spanning from January 1 to December 3, 2006 were acquired from the NASA Earth Observation System Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/). For each composite period, the MODIS NDVI data were extracted for each tile and then mosaicked and reprojected from the Sinusoidal to the Albers Conical Equal Area projection. The reprojected mosaics, 22 in total (composite date of December 19 was missing), were then sequentially stacked by composite period and subset to the state's boundary to produce the final time-series data sets of Nebraska.

2.3.2 Field Site Database

A field site data set for specific crop types was created using the 56-m 2006 Nebraska CDL, produced by USDA-NASS (USDA-NASS, 2007). The 56-m 2006 CDL was derived from ground-based data for crops growing within the state at the time of the June survey, using IRS AWiFS imagery and Common Land Unit (CLU) as a source of training and validation data. The classification accuracy was generally between 85% and 95% for agricultural-related land cover categories (USDA-NASS, 2007). The producer's accuracy (Table 2.1) for corn, soybeans, and winter wheat was higher than 95%; while alfalfa, millet, and sorghum had accuracy of 79%, 63%, and 52%, respectively. Sunflowers had an exceptionally low accuracy of 33%.

Table 2.1 Nebraska 2006 statewide percent correct, commission error and kappa statistics extracted from Nebraska accuracy assessment table (USDA-NASS, 2007). NOTE: User's accuracy and fallow class were not included in the CDL accuracy statistics table.

Crop Cover	Producer Accuracy %	Commission Error	Conditional Kappa
Alfalfa	79.03	11.28	78.12
Corn	97.75	4.55	95.12
Millet	63.28	35.14	62.95
Sorghum	51.59	21.44	51.03
Soybeans	96.73	5.38	95.50
Sunflowers	32.85	32.42	32.75
Winter Wheat	94.93	10.04	94.29

Although problems were anticipated, possibly arising from the quality of field data and inaccuracies in producing the crop specific digital layers, it was assumed that the 2006 Nebraska CDL product would be suitable for extracting field sites.

The seven crops and fallow land cover type raster layers were separated from the CDL by creating new raster files using a raster calculator in Spatial Analyst, a GIS extension tool. Each separate layer was converted from raster into polygon layer using a GIS raster to polygon conversion tool. Subsequently, the size of each polygon was calculated using pre-logic Visual Basic for Applications (VBA) script code. This was necessary to reduce the number of polygons for each crop layer to a manageable size. Therefore, the average size of the smallest contiguous polygon for the most predominant crops (alfalfa, corn, soybeans, and winter wheat) was set at 56.25 ha (approximately 9 MODIS 250-m pixels), and 37.5ha (approximately 6 MODIS 250-m pixels) for the less predominant crops for which smaller acreages were planted (grain millet, sorghum, and sunflower) and fallow.

A three-composite-date MODIS NDVI raster (e.g., Figure 2.2) in which the crop was expected to have attained considerable growth and maturation was created for each cover type and was used as a background to the crop polygon layers. Table 2.2 lists the composite date range used for each crop. Each crop's polygons that overlapped with the MODIS NDVI raster for the three composite dates were selected. The selected polygons corresponded to the polygon size of above 500 ha for corn and soybeans; above 100 ha for grain millet and winter wheat; above 45 ha, 40 ha, and 30 ha for alfalfa, sorghum, and sunflower, respectively. The MODIS NDVI raster for the three dates of June 29, July 28, and August 29, were used as a background for the fallow polygon layer. The fallow profile in Kansas (Wardlow *et al.,* 2007) was used as guide in the selection of the composite dates. During this time period fallow had the lowest NDVI values in comparison to other cover types. It was assumed that selecting low NDVI values would be ideal in representing fallow sites. The fallow polygons that overlapped with the low MODIS NDVI values were selected. The polygon size of these selected was greater than 85 ha.

Table 2.2 A listing of the composite date range used for each crop for 2006

Crop Type	**Composite dates**
Alfalfa	April 7, May 9, and May 25
Corn	July 12, July 28, and August 13
Grain Millet	July 12, August 13, and August 29
Sorghum	July 12, August 13, and August 29
Soybeans	July 12, July 28, and August 13
Sunflower	July 12, August 13, and September 14
Winter Wheat	April 7, May 9, and May 25
Fallow	June 26, July 28, and August 29

The centroids for each polygon used in the analysis was computed and examined to determine whether its computed location as accurate. The accuracy was assessed by looking at the geographic location of each centroid to determine whether it appeared near the center of each polygon (Figure 2.2). Centroids that fell just outside or inside the polygon boundaries were manually shifted to the middle of the polygon to ensure that the NDVI values extracted at the centroid locations were away from the polygon edges which would result in the use of NDVI values from mixed pixel cover types. Centroids that fell too far outside the contiguous polygons were removed from the database.

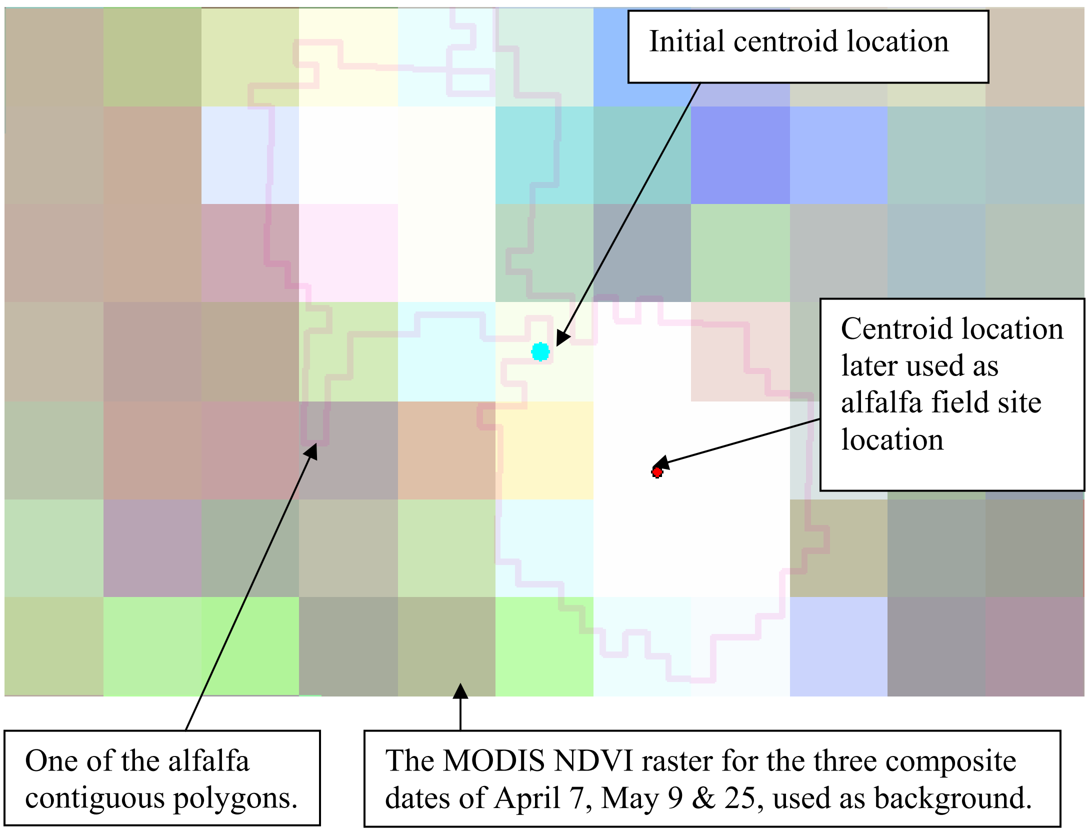

Figure 2.2 An illustration of locational criteria for alfalfa using alfalfa polygon layer and MODIS NDVI raster for the three composite dates in which alfalfa was expected to have attained considerable growth and maturity.

The MODIS NDVI grid for the three composite dates for each of the eight crop and fallow layers were used as a background to aid in the selection of a suitable single 250-m pixel to represent each field site. The geographic locations of 1,576 initial centroids (Table 2.3) that meet the locational criteria as demonstrated above were then considered as the locations of each crop's initial field sites.

Table 2.3 Number of land cover contiguous polygons and initial field sites by crop type

Crop Type	Number of polygons after conversion	Minimum average size of polygon (Ha)	Number of Selected Polygons	Polygon average size (Ha)	Initial number of field sites
Alfalfa	31,023	56.25	1158	>45	266
Corn	169,600	56.25	929	>500	380
Grain Millet	13,251	37.5	315	>100	97
Sorghum	7,058	37.5	271	>40	91
Soybeans	95,069	37.5	319	>500	310
Sunflower	1,392	37.5	111	>30	64
Winter Wheat	61,622	56.25	1146	>100	286
Fallow	78,6191	37.5	144	>85	82
Total					1576

2.3.3 Kansas Average NDVI Profiles

A total of 2,800 verified field sites in Kansas were used by Wardlow *et al.* (2007) to extract time-series NDVI values from 2001 MODIS data. Average NDVI profiles were created for the five major crops of alfalfa, corn, grain sorghum, soybeans, and winter wheat. To refine the curves of these crop types, the profiles were visually evaluated to verify that their spectral characteristics were consistent with the general phenology of the crop type reported by the FSA. Each refined curve was considered a standard NDVI profile for the respective crop type in Kansas. Due to the rigorous process of selecting the field sites and curve refinement against field truth, the Kansas profiles are considered to be a valid standard against which Nebraska NDVI curves could be compared. The temporal shifts in a crop's NDVI signature were however observed across Kansas (Wardlow *et al*., 2007). Although noticeable curve time-shifts were anticipated between Kansas and Nebraska because of variation in precipitation and length of crop growing season, it was expected that the general curve patterns would be the same.

2.3.4 Methods

A total of 1,576 field sites representing the eight cover types under investigation were used as a basis for extracting time-series NDVI values. To refine the reference data set, the extracted NDVI data from the ' initial field sites' for each crop type (excluding fallow) were subjected to cluster analysis (Romesburg, 2004), using *k-means* clustering, as a way of evaluating variability among field sites within each crop type. A *k-means* clustering analysis was chosen because (i) it is an exploratory data analysis tool that is commonly used to discover structures in the data without providing an explanation or interpretation; (ii) the researcher has the advantage of specifying the number of clusters in advance, then calculates how to assign cases to the *k* clusters; and (iii) this type of clustering is much less computer-intensive, therefore it is preferred when the data sets are very large.

Several cluster sizes were tried and in each case profiles were plotted and visually examined. Since some larger cluster sizes did not have members, the maximum cluster size of 10 was assumed adequate. Three cluster data sets of 10, 7 and 3 clusters were generated for crops with a large number of field sites (e.g. alfalfa, corn, soybeans, and winter wheat), while for crops with a relatively small number of field sites (e.g. millet, sorghum, and sunflowers) two data sets of 5 and 3 clusters were generated. After clustering, each cluster's NDVI profiles for each specific crop was created and visually compared to the known MODIS-based profiles of similar crops in Kansas. Due to the fact that data sets with fewer clusters tended to conceal subtle differences among field sites, the 10-cluster data set for crops with large number of field sites and 5-cluster data set for crop with a relatively small number of field sites were deemed adequate in revealing the field sites' variability. Cluster profiles that were consistent with the spectral-temporal profiles of a similar crop in Kansas were aggregated to represent crop-specific, state-level time-series NDVI profiles for Nebraska. When the field sites in each cluster were mapped, the pattern did not show any regionalization. Using this refining process, cluster profiles that were outliers for sites atypical of Kansas's crop phenology were identified and removed. Profiles of millet and sunflower were not available for Kansas. Millet cluster profiles were evaluated independently and a profile that was consistent with the general seasonal pattern of an annual crop growth cycle was selected. A typical sunflower profile was selected after sunflower cluster profiles were compared to the Landsat-based profiles demonstrated in Odenweller & Johnson (1984). After completing this field site refinement process, there were 1,288 sites retained for further analysis. These sites hereafter will be referred to as 'final' field sites (Table 2.4, Fig. 2.3).

Table 2.4 Number of "initial" and "final" field sites by crop type.

Crop Type	Initial Field Sites	Final Field Sites
Alfalfa	266	226
Corn	380	370
Grain Millet	97	19
Sorghum	91	83
Soybeans	310	303
Sunflower	64	20
Winter Wheat	286	185
Fallow	82	82
Total	1576	1288

Figure 2.3 Retained field site locations by crop type

2.4 RESULTS and DISCUSSION

The following results and discussion are presented within the context of a crop's annual growth cycle, generally divided into three key periods: 1) the emergence of vegetation or green up (ascending phase), 2) peak growth, flowering and formation of seed (plateau), and 3) maturity, senescence, and harvesting (descending phase). The NDVI cluster profiles of alfalfa, winter wheat, corn, sorghum, and soybeans were visually compared to the known MODIS-based profiles of similar crops in Kansas. Millet cluster profiles were independently evaluated based on the crop's expected characteristic annual form, while sunflower clusters were compared to the known Landsat-based sunflower profile (Odenweller & Johnson, 1984) from the fields in the Corn Belt of the U.S.A.

Alfalfa:

Figure 2.4 shows that in Kansas, the alfalfa profile (Wardlow *et al*., 2007) is characterized by a steep ascending phase because of the rapid increase in NDVI during the early spring, multiple 'growth and cut' cycles, and a gently descending phase. The profiles of clusters 5, 8, 9, and 10 in the Nebraska data set, although relatively higher, displayed a general form that was consistent with the profile of alfalfa in Kansas. Each cluster profile showed minor variations in the timing of green up span of the growing period, and in the 'growth and cut' cycles. The 'growth and cut' cycles were not synchronous but more pronounced at different time periods because of variations in the number, timing, and quantity of foliage cuttings per year. The descending phase for clusters 5 and 9 occurred relatively earlier than the other clusters.

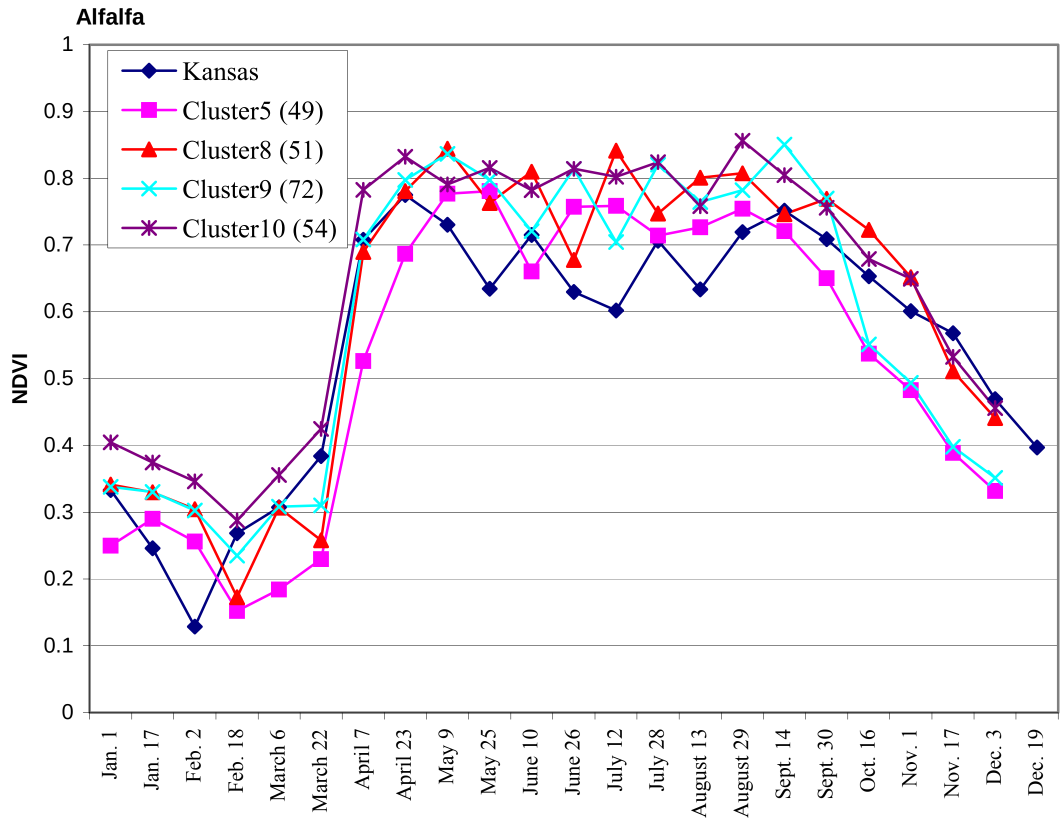

Figure 2.4 Alfalfa. Time-series average NDVI profiles of Kansas and retained Nebraska clusters. Nebraska clusters have numbers of retained field sites in parentheses.

Since the NDVI profiles of clusters 5, 8, 9, and 10 were consistent with the Kansas alfalfa profile, their field sites totaling 226 constituted the alfalfa reference data set for Nebraska.

The profiles of clusters 1, 2, 3, 4, and 7 were not consistent with the alfalfa profile in Kansas (Fig. 2.5). Clusters 1 and 7 had shorter growing period, while clusters 2 and 3

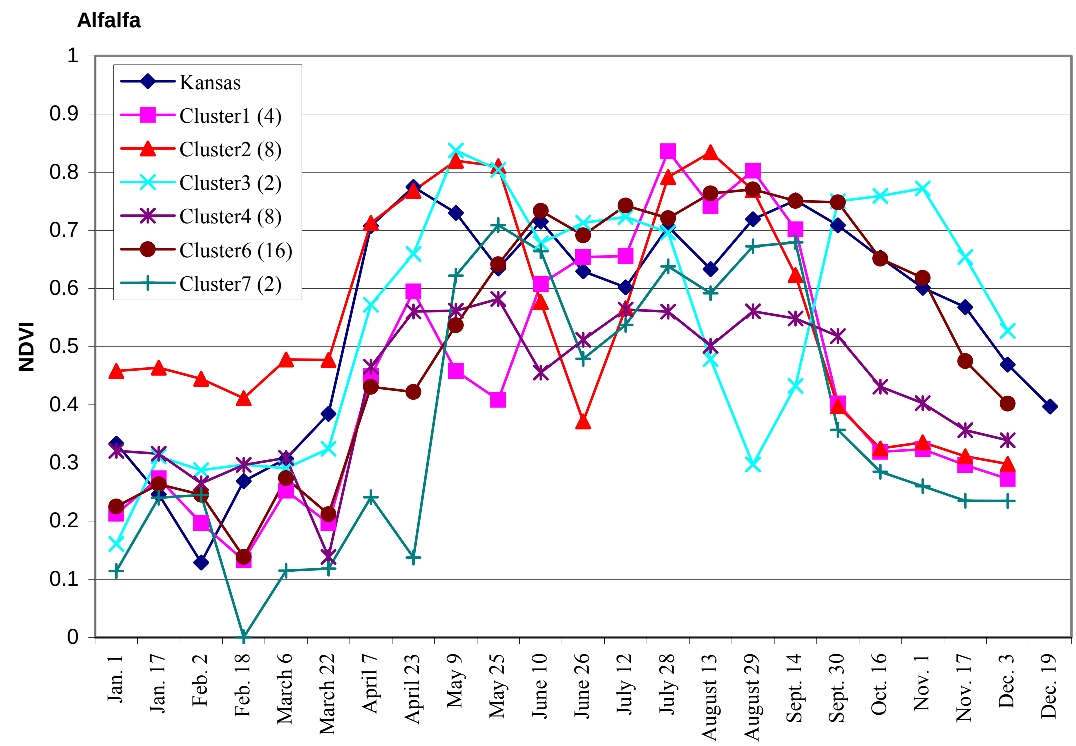

Figure 2.5 Alfalfa. Time-series average NDVI profiles of Kansas and rejected Nebraska clusters. Nebraska clusters have numbers of rejected field sites in parentheses.

displayed what is apparently a double cropping pattern. The descending phase of clusters 1, 2, and 7 was steeper than for the other clusters with pronounced depressions possibly due to extended harvesting period. Although clusters 4 and 6 were similar to alfalfa, cluster 4 had a generally low profile possibly because of less vigorous growth or drought stress. Cluster 6 indicates that possibly there was drought stress during the early phase of the crop's growth and its general pattern did not display pronounced multiple 'growth and cut' cycles. Because of the cluster profiles' inconsistent patterns, their field sites, 40 in total, were removed from the alfalfa reference data set.

Winter Wheat

Winter wheat in Kansas is characterized by rapid growth and maturity in spring with a gentle ascending and shaper descending phase, and a second smaller NDVI peak in November and December corresponding to the emergence and growth of the following year's crop (Fig. 2.6).

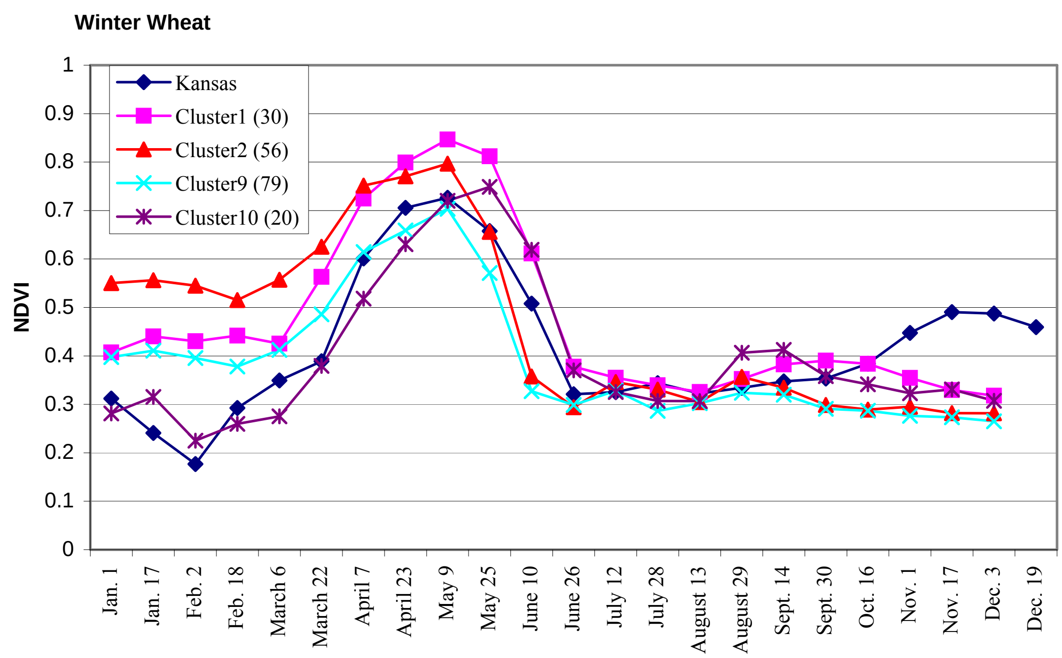

Fig 2.6 Winter wheat. Time-series average NDVI profiles of Kansas and retained Nebraska clusters. Nebraska clusters have numbers of retained field sites in parentheses.

Winter wheat cluster profiles 1, 2, 9, and 10 (Fig. 2.6) seemed to be consistent with the Kansas winter wheat profile during spring, although the profiles of clusters 1, 2, and 10 were relatively higher than the Kansas profile. Although the key growth phases for all clusters occurred at different time periods, the form of their ascending phase, peak greenness, and descending phase were typical of the Kansas profile in the spring. These profiles represented a winter wheat-fallow cropping pattern. Field sites for these profiles totaling 185 were selected to represent winter wheat reference data for Nebraska.

Profiles of clusters 3, 4, 5, 6, 7, and 8 (Fig. 2.7) were considered atypical of the Kansas winter wheat profile. Cluster profile 4 looks like either fallow or failed wheat. With respect to cluster 8, the profile was not typical of the winter wheat-fallow cropping pattern and may possibly be an alfalfa crop. Clusters 3, 5, 6, and 7 experienced increased NDVI values during the summer and early fall possibly due to significant weed growth or different soil background. Many wheat areas in Nebraska are on highly sandy soils that may produce a higher 'latent' NDVI signal than locations in Kansas.

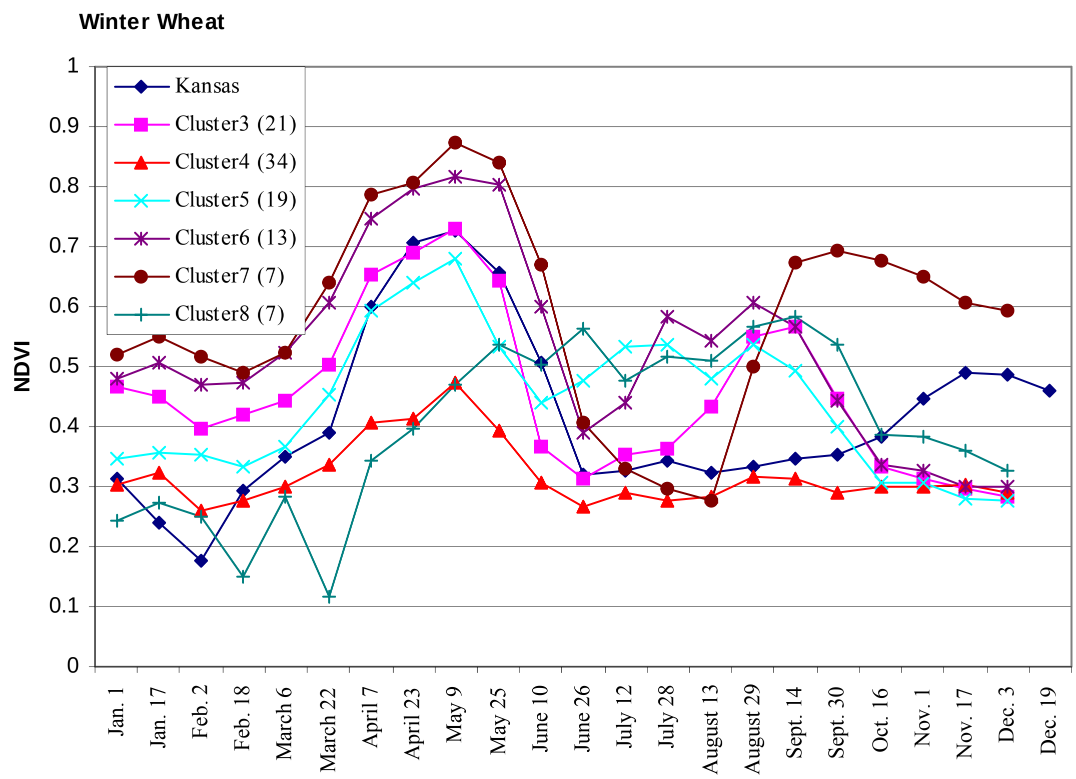

Fig. 2.7 Winter wheat. Time-series average NDVI profiles of Kansas and rejected Nebraska clusters. Nebraska clusters have numbers of rejected field sites in parentheses.

Field sites for the above atypical cluster profiles, 101 in total, were therefore removed from the winter wheat reference data set.

Corn

Corn's spectral profile in Kansas assumes a very distinctive profile form (Fig. 2.8), reaching a peak relatively early in the crop's development cycle. Following the peak, the profile drops gently and then levels off.

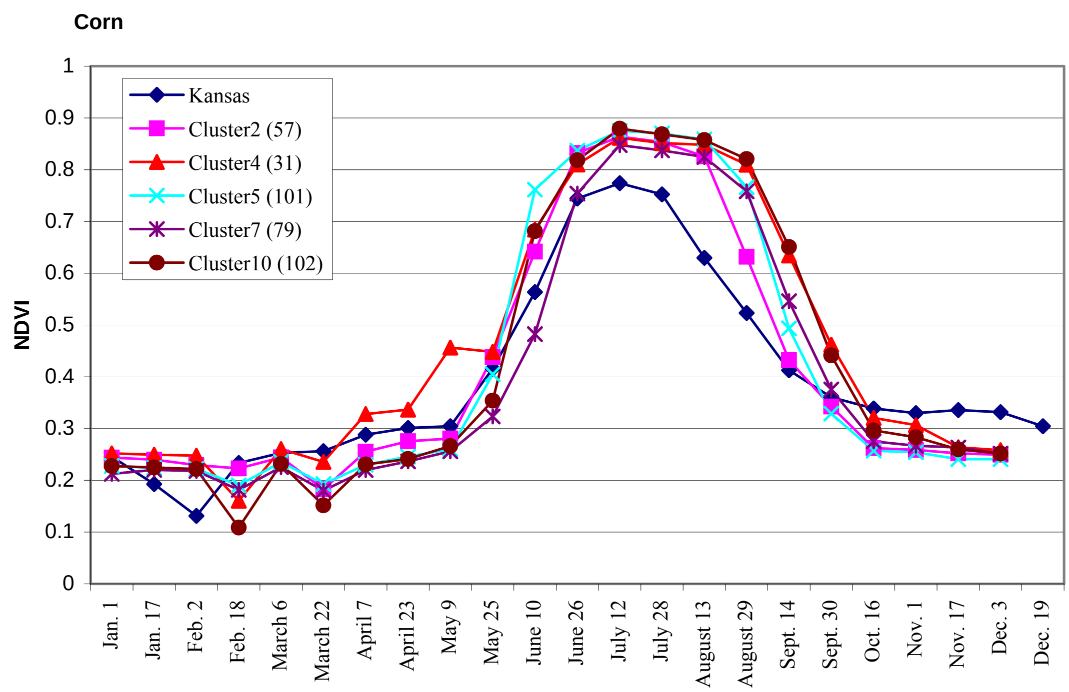

Fig. 2.8 Corn. Time-series average NDVI profiles of Kansas and retained Nebraska clusters. Nebraska clusters have numbers of retained field sites in parentheses.

Profiles of clusters 2, 4, 5, 7, and 10 (Fig. 2.8) are relatively higher than the Kansas one. The profiles have a generally rapid-ascending phase, broader peak greenness period, and sharper descending phase. These profiles were considered to be good representation of the corn development cycle in Nebraska. Therefore, the respective field sites totaling 370 on which these profiles were developed constituted the corn reference data set for the state.

Clusters whose general profiles were not typical of the Kansas corn profile included clusters 1, 3, 6, 8, and 9 (Fig. 2.9). They all displayed variations not consistent with corn growth cycle.

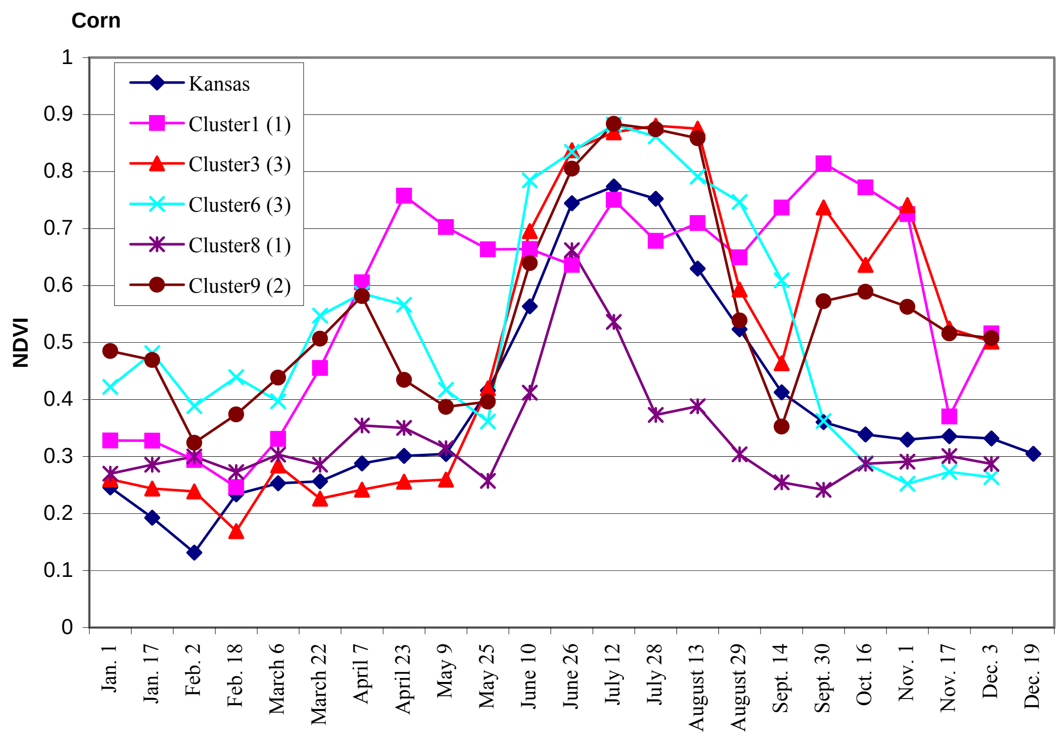

Fig. 2.9 Corn. Time-series average NDVI profiles of Kansas and rejected Nebraska clusters. Nebraska clusters have numbers of rejected field sites in parentheses.

Cluster 1 appears more likely to be an alfalfa crop profile than a corn profile, while cluster 8 did not have the general bell-shaped form characteristic of corn growth cycle and may represent a failed crop or the cutting of corn for silage. Although clusters 3 and 9 displayed profiles that are in general agreement with corn's growth cycle, they showed minor peaks possibly associated with weeds in the spring or in the fall. Cluster 6 had a winter wheat-corn signature. The variant form of the profiles of these clusters and the small number of sites involved necessitated the removal of 10 field sites from the corn reference data set.

Sorghum

Sorghum's profile (Fig. 2.10) in Kansas assumes a gentle ascending phase similar to other summer crops. Sorghum typically is characterized by a later green up due to later planting date than other summer crops and a longer, more gradual decrease in NDVI during the descending phase than summer crops.

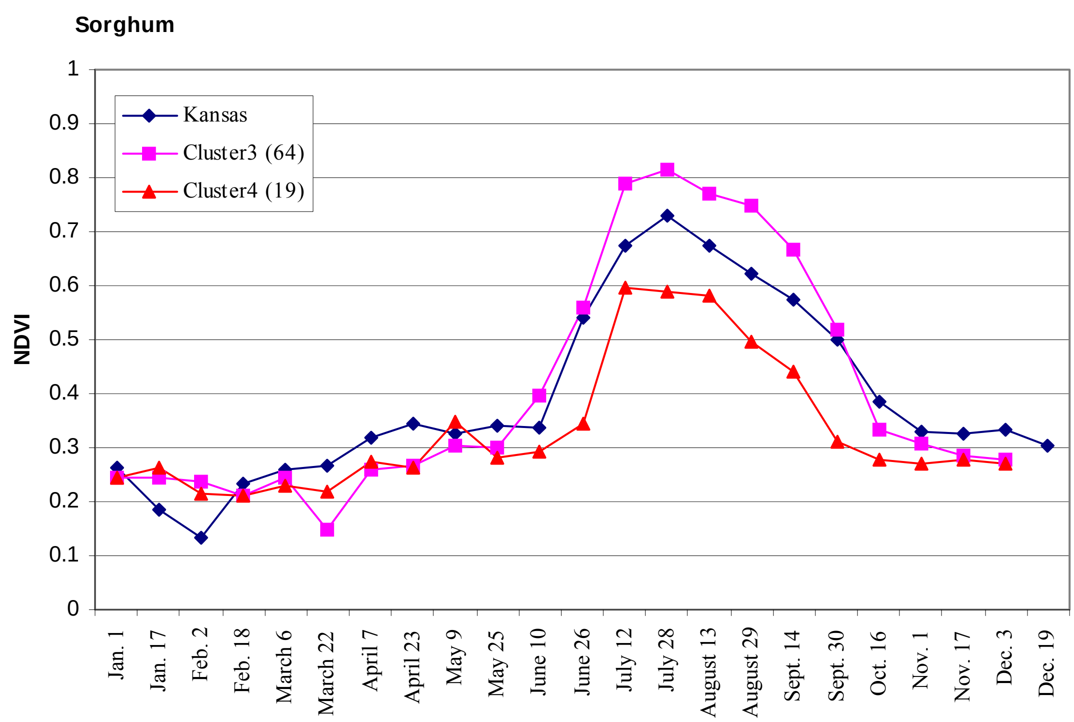

Fig. 2.10 Sorghum. Time-series average NDVI profiles of Kansas and retained Nebraska clusters. Nebraska clusters have numbers of retained field sites in parentheses.

The gradual drop following the peak seems to be indicative of the senescence behavior of sorghum. During this period, the leaves are relatively green and often remain partially green at harvest (Vanderlip *et al*., 1998). Profiles of clusters 3 and 4 (Fig. 2.10) were consistent with the sorghum profile in Kansas. The profile for cluster 3 was much higher than the one for cluster 4, possibly because of differences in the crop varieties, with the latter suggesting a shorter growing period variety. A total of 83 field sites represented by the two cluster profiles, were then retained as the sorghum reference data set.

Figure 2.11 shows the three cluster profiles that were not typical of profiles for clusters 3 and 4, nor the sorghum growth cycle in Kansas. Both profiles for sorghum clusters 1 and 5 show likely double cropping with a well-pronounced bi-modal pattern for the latter.

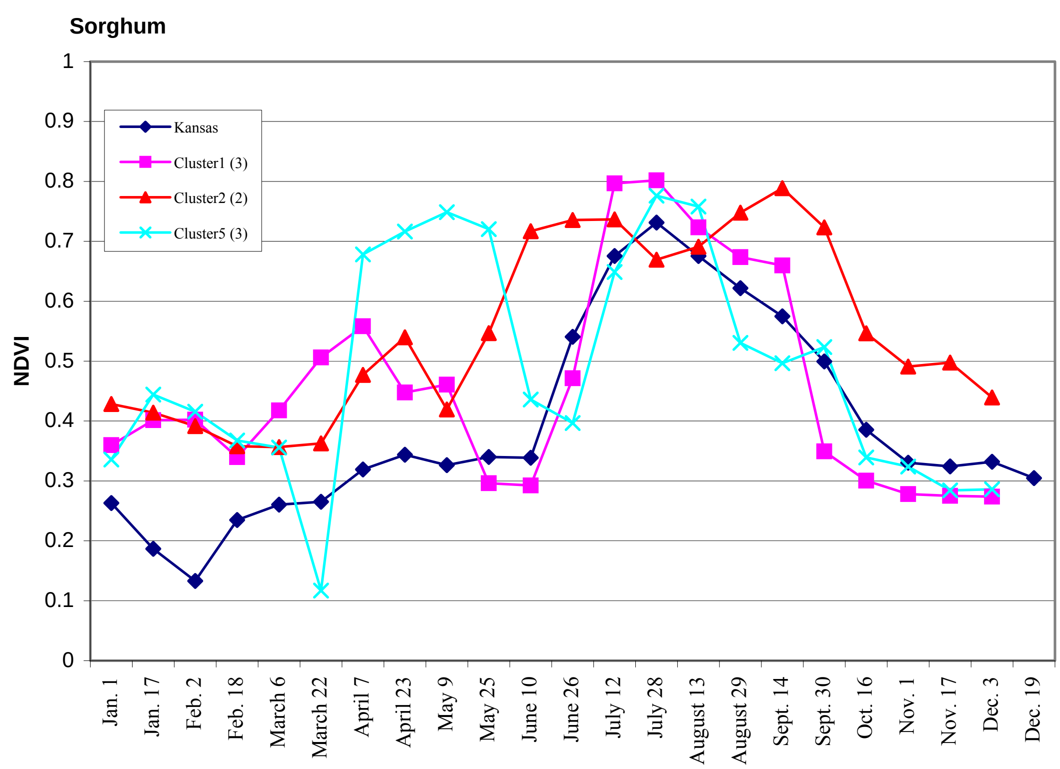

Fig 2.11 Sorghum. Time-series average NDVI profiles of Kansas and rejected Nebraska clusters. Nebraska clusters have numbers of rejected field sites in parentheses.

Although cluster 1 was indicative of the general development trend of sorghum, the profile revealed a relatively higher pre-season NDVI signal due to either winter wheat or a significant amount of pre-season weeds. A similar trend was observed over the same fields in Kansas (Wardlow et al., 2006). Cluster 2's response appeared to correspond to a non-crop NDVI signal. Eight field sites for these clusters were removed from the reference data set because their profiles were inconsistent with the general sorghum growth cycle.

Soybeans

The soybean profile (Fig. 2.12) in Kansas generally has a rapid descending pattern due to the rapid drying and loss of leaves as compared to corn and sorghum, and tends to reach higher maximum amplitude than other summer crops. The higher peak greenness occurs well into the crop's development cycle because of its continued vegetative growth until flowering.

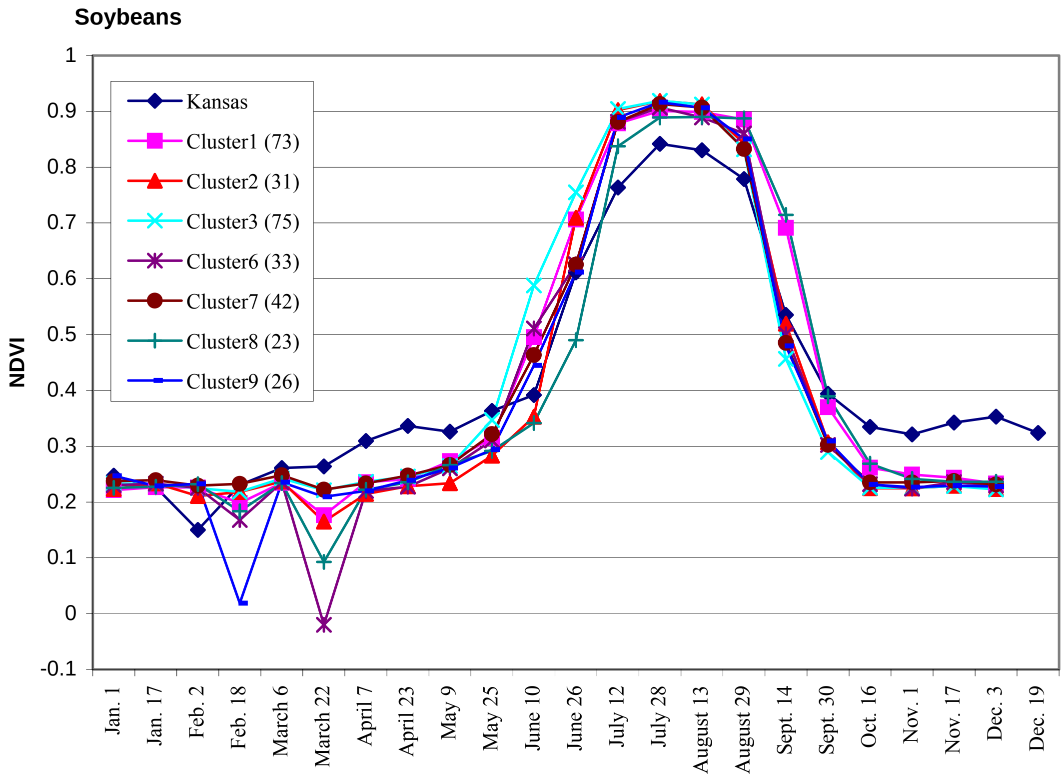

Fig 2.12 Soybeans. Time-series average NDVI profiles of Kansas and retained Nebraska clusters. Nebraska clusters have numbers of retained field sites in parentheses.

Seven cluster profiles, 1, 2, 3, 6, 7, 8, and 9 (Fig. 2.12) had a relatively steeper appearance with high maximum amplitude. Since these clusters were a good representation of the Kansas profile and the general soybeans growth cycle, the field sites, totaling 303, from which the NDVI values were extracted constituted the soybeans crop reference data set.

Figure 2.13 shows cluster profiles that were considered to be inconsistent with the selected cluster profiles in Fig. 2.12.

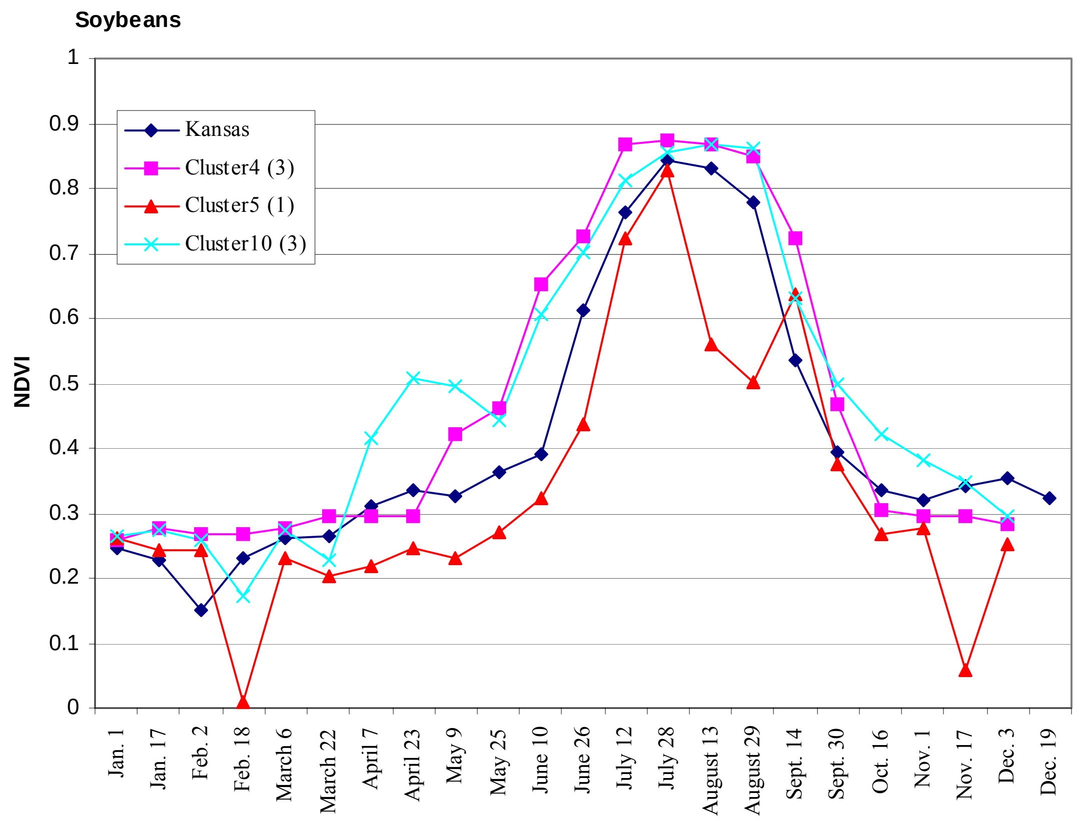

Fig. 2.13 Soybeans. Time-series average NDVI profiles of Kansas and rejected Nebraska clusters. Nebraska clusters have numbers of rejected field sites in parentheses

Although the profile of cluster 4 somewhat resembled the profiles of retained clusters, its pattern deviated slightly. Since both cluster profiles 4 and 10 had a small sample size and depicted a relatively longer growing phase with relatively lower maximum amplitude, earlier and gradual green up and senescence, in comparison to the retained clusters, they were considered poor candidates. The soybeans cluster profile 5, based on one field site, was not a good representative of the soybeans growth cycle. Therefore, 7 field sites for cluster profiles 4, 5, and 10 were removed from the database.

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Sunflower

Odenweller and Johnson (1984) illustrated a Landsat-based sunflower profile representative of the patterns and trends that were observed in the sample segment 185, Traverse, Minnesota (Figure 2.14). GRABS (Greenness Above Bare Soil) on the y-axis is the vegetation indicator, which is equivalent to the Greenness component of the Tasselled Cap Transformation minus a discriminant placed at the top of the bare distribution (Odenweller and Johnson, 1984). Odenweller and Johnson (1984) state that the green vegetation detection threshold for GRABS is theoretically equal to a value of zero, a slightly higher threshold of 6.0 is used in order to increases the probability that only values indicative of green vegetation will be above the threshold.

Sharp and steep ascending and descending phases, with a single peak, characterized the form of the profile. The GRABS value of above 6.0 in late-June followed by a rapid increase in values to the maximum of above 45 in July, corresponded to the crop emergence, rapid growth, and maturity. The values dropped between August and early September indicative of senescence.

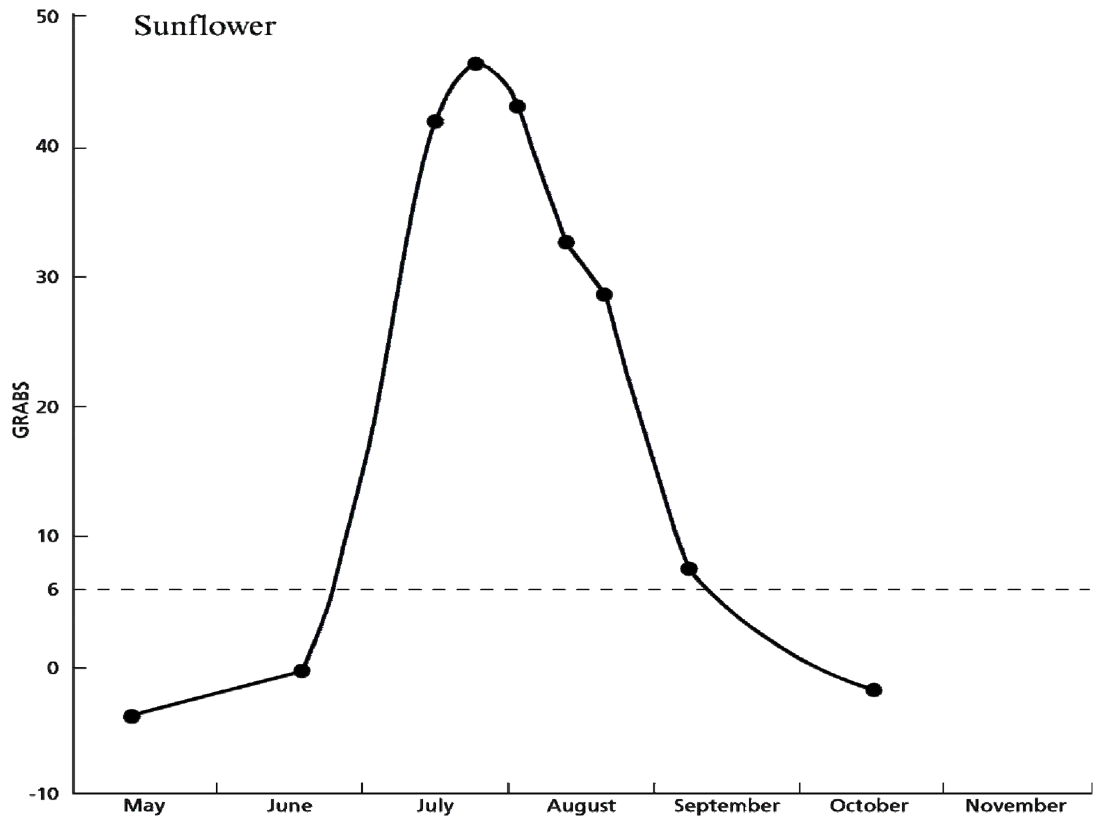

Figure 2.14 A Landsat-based sunflower profile manually interpolated from existing data points, Traverse, Minnesota (adapted from Odenweller and Johnson, 1984).

After the five sunflower cluster profiles (Fig. 2.15) were visually compared to this known Landsat-based profile (Figure 2.14), only the profile for cluster 4 was deemed to be consistent with this general sunflower profile. Cluster profiles 2 and 3 which were based on a very small number of field sites, did not correspond well to the general sunflower profile. Sunflowers are commonly grown in the northwest and southwest of Nebraska. In these lower rainfall areas, one of the cultural practices is to summer fallow fields previously planted to sunflowers prior to planting winter wheat (Thomas *et al.,* 2003). Cluster profiles 1 and 5 seem to indicate such a cultural practice on the field sites constituting these clusters since there was clearly no crop present during the summer, or may as well indicate crop failure.

Field sites for cluster profiles 1, 2, 3, and 5 were removed from the sunflower database leaving a total of 20 field sites representing cluster profile 4.

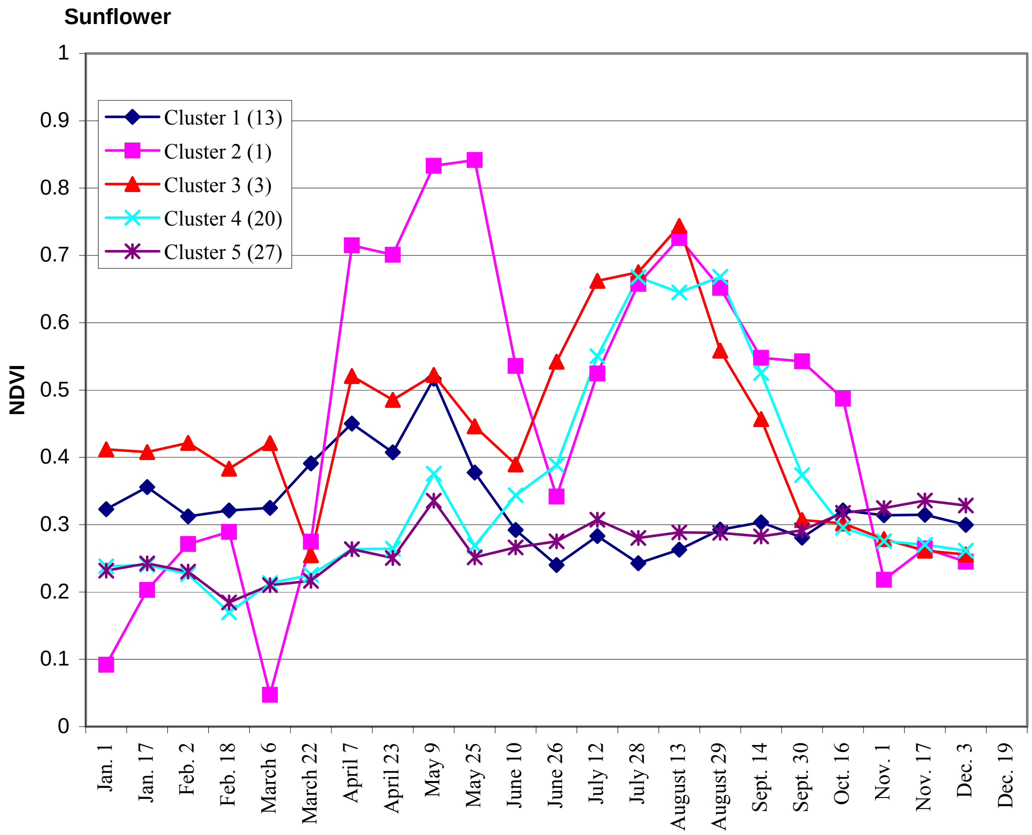

Fig. 2.15 Sunflower. Time-series average NDVI profiles of Nebraska clusters with numbers of field sites in parentheses. No sunflower sample curves were available from Kansas for comparison.

Millet

Proso millet (*Panicum miliaceum L*), commonly grown in Nebraska, is a short-season crop that often requires 60 to 90 days from seeding to maturity and is generally grown as a late-seeded, short-season summer crop. The crop is planted between May and June and is usually harvested as grain in September (Baker, 2003; University of Nebraska Cooperative Extension).

Millet cluster profiles (Fig. 2.16) were evaluated independently to ascertain the extent to which the profiles were consistent with the general characteristic pattern of an annual short-season crop growth cycle described above. All the profiles show a minor peak, possibly associated with weeds in the spring. With the exception of cluster profile 2, all profiles vary in the timing of the emergence of vegetation, the form of the peak, and the senescence trend. Cluster 4 depicted a steep ascending phase in June; a generally flat peak consistent with the length of the growing period of millet, and a steep descending phase associated with crop harvesting in September. The profiles for clusters 2 and 3 may indicate crop failure and low crop density or foliage, respectively. Clusters 1 and 5 have a sudden NDVI decline after peak greenness, thus suggesting haying.

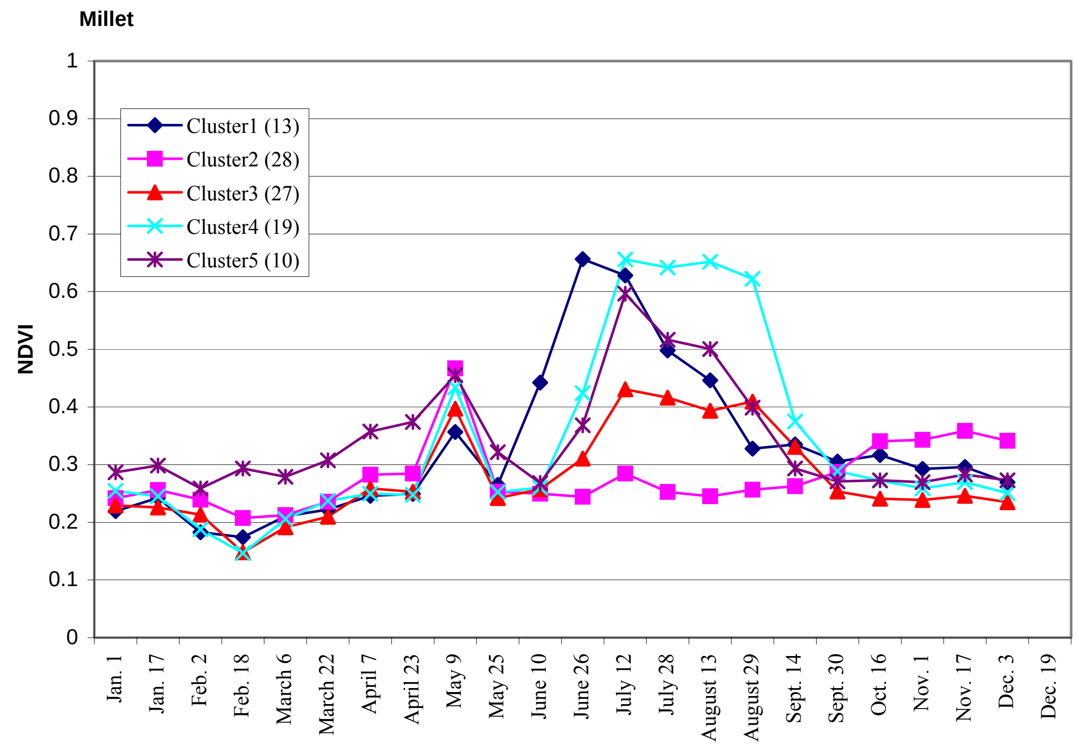

Fig. 2.16 Millet. Time-series average NDVI profiles of Nebraska clusters with numbers of field sites in parentheses. No millet sample curves were available from Kansas for comparison.

Since cluster 4 was deemed to be consistent with the general characteristic pattern of the grain millet growth cycle, 19 field sites representing this cluster profile were retained as grain millet reference data set, while 23 field sites representing cluster profiles 1 and 5 constituted forage millet data set. The rest of the clusters were removed from the database.

2.5 CONCLUSIONS

The aim of this research was to develop robust ways of creating and refining a reference data set for remote sensing-based research work, when the reference data set is unavailable. In this research, strategies of reference data generation were investigated by using GIS operations, and reference data refinement using *k-means* clustering and visual assessment of each crop's NDVI cluster profiles, as essential steps for developing a crop reference data set for Nebraska. The approach used in the generation of reference data involving the use of centroids as a basis for locating each crop's field sites, proved to be feasible and very convenient. However, the process of moving centroids to suitable locations when they fell outside the contiguous polygons was time consuming. Clustering of the NDVI values and subsequently plotting cluster profiles for visual comparison with other known crop profiles enabled the data to be analyzed in its original form. The amplitude and specific form of the profiles (i.e. ascending and descending phases) provided the key for refining a label to the crop cluster profiles or removing it from the reference data set if it was not representative of the target crop cover class. Each crop's NDVI cluster profiles that resembled the known phenological pattern of the same crop in neighboring Kansas were aggregated to represent crop-specific, state-level multi-temporal NDVI profiles for Nebraska. Only a relatively small number of outliers and sites atypical of the good curves however were identified and removed. Of an initial set of 1,576 sites, field sites totaling 1,288, whose average NDVI profiles appeared to be consistent with the known crop profiles, constituted the crop reference data set for Nebraska. This research has demonstrated that it is possible to devise an alternative reference data set and refinement plan that redresses the unexpected loss of access to training and validation data in the U.S. Apart from contributing to the existing body of knowledge on ground reference data collection protocols, the methodology developed during this study will be especially useful in regions were reference data sets are often not available such as Zambia, a country in need of up-to-date LULC maps for resource planning and management purposes.

In future research, (i) attempts should be made to automate the process of re-locating centroids that fall outside the polygons, and (ii) instead of visual profile comparison only, alternative mathematical techniques (e.g., curve fitting) should be explored to describe and compare each crop's known profile and the MODIS-based NDVI profile forms.

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Chapter 3

DATA EXPLORATION: SPECTRAL CHARACTERIZATION OF MAJOR CROPS USING MULTI-TEMPORAL MODIS 250-METER NDVI DATA IN NEBRASKA

CHAPTER SUMMARY

A considerable amount of land in the Great Plains of the USA has been converted to intensive agriculture, thus making the region one of the major crop producing areas in the world. The crop related land use/land cover (LULC) types in the Great Plains display different phenological patterns in response to recurring natural and cultural factors, which in turn determine crop-specific spectral profile characteristics. Therefore, there is a need for spectral profile analysis efforts on a repetitive basis. Spectral profile analysis is essential because it facilitates the characterization of the constantly changing environment and it is often a preliminary phase in LULC classification and mapping efforts.

The aim of this study was to extend work previously done in Kansas to Nebraska, using different exploratory approaches, to further investigate the potential of MODIS NDVI 250-m data in agricultural-related land cover research in the Great Plains of the USA. The objective of the research was to evaluate the applicability of time-series MODIS 250-m NDVI data for crop-type discrimination in Nebraska.

A *k*-means cluster analysis of NDVI values from 1,288 field sites representing alfalfa, corn, grain millet, sorghum, soybeans, sunflower, winter wheat, and fallow; was performed to identify validation sites with time-series NDVI spectral profiles characteristic of the major crop types grown in Nebraska. Graphical and statistical analyses were performed to evaluate the applicability of time-series MODIS 250-m NDVI data for crop type discrimination. Class separability among specific crop types in the time-series MODIS 250-m NDVI was investigated graphically using time-series of periodic-specific ± 1 standard deviation of crop-specific NDVI values, and numerically using the Jeffries-Matusita (JM) distance statistic.

The results show that each crop type had a distinctive MODIS 250-m NDVI profile corresponding to the crop calendar. A visual and statistical comparison of the average NDVI profiles showed that the crop types were separable at different times of the growing season based on their phenology-driven spectral-temporal differences. Winter wheat and alfalfa, winter wheat and summer crops, and alfalfa and summer crops were clearly separable. Specific summer crop types were not easily distinguishable from each other due to their similar crop calendars. Their greatest separability however occurred during the initial spring green up and/or senescence plant growth phases.

3.1 INTRODUCTION

A considerable amount of land in the Great Plains of the USA has been converted to intensive agriculture (Gunderson, 1981; Pieper, 2005; Sims, 1988), thus making the region one of the major crop producing areas in the world (Birdsall and Florin, 1998). The crop related land use/land cover (LULC) types in the Great Plains display different phenological patterns, which in turn determine the crop-specific spectral profile characteristics (Bauer *et al*., 1980; Daughtry *et al*., 1984; Wardlow *et al*., 2007). However, changes in climate and groundwater availability (USGCRP, 2000; Ojima, 1999), and changing trends in land use management practices and government land use policies (Parton *et al*., 2007) pose serious challenges to the region's long-term agricultural sustainability. These recurring challenges in the Great Plains' agro-ecosystems are reflected in the time-series spectral profiles of the crop-related LULC types, hence the need for spectral profile analysis efforts on a repetitive basis. The spectral profile analysis is essential because it facilitates the characterization of the constantly changing environment, and it is often the preliminary phase in LULC classification and mapping efforts.

Remote sensing has been recognized as a valuable tool for viewing, analyzing, characterizing, mapping and making decisions about our ever-changing environments (Schowengerdt, 1997). Remote sensing of LULC is based on the principles of interaction between matter and electromagnetic energy. For any type of land cover, the amount of incoming solar radiation that is reflected, absorbed, and transmitted will vary with wavelength (Curran, 1985; Campbell, 1987; Lillesand and Kiefer, 1987; Sabins, 1987). This basic principle makes it possible for various kinds of land cover types to be recognized and distinguished from each other by differences in spectral reflectance.

Satellite-based remotely sensed data have a wide range of agricultural applications due to their unique multi-spectral and multi-temporal characteristics. The applications include spectral characterization of crops, estimation and monitoring of biophysical characteristics of crops/vegetation, early estimates of crop yield and production, crop classification and mapping, the monitoring of crop development/condition, and crop canopy activity monitoring. The successes that have been achieved by remote sensing technology in agricultural applications can be attributed partly to a better understanding of spectral profiles of different crops types in varying agro-ecological systems (Bauer *et al*., 1980; Daughtry *et* *al*., 1984; Lo *et al*., 1986; McAdam, 1997; Odenweller and Johnson, 1984; Wardlow *et al*., 2007; Wiegand *et al*., 1990; 1992). The varying spectral profiles of crops are due to the fact that each crop has a well-defined crop calendar with specific planting times (USDA, 1997) and unique seasonal growth patterns (Christ, 1984; Odenweller and Johnson, 1984; Reed *et al*., 1994; Wardlow *et al*., 2007).

Although spectral-temporal profiles for different crops under different environmental conditions will vary, all green plants will follow the general trend of decreasing red reflectance and increasing near-infrared reflectance with an increase in plant cover and phytomass, and the converse for decreasing or senescent plant cover. Various ratios and combinations of red and near-infrared reflectance, collectively called vegetation indices (VI) (Kauth and Thomas, 1976; Perry and Lautenschlager, 1984; Richardson and Wiegand, 1977; Rouse *et al*., 1973; Tucker *et al*., 1979), have been developed primarily for the study of vegetation and as result, are often used as a single surrogate indicator of plant development and condition assessment (e.g. vigor and water stress) (Allen *et al*., 2002; Bauer, 1985; Doraiswamy *et al*., 2004; Thenkabail et al., 1992; Tucker et al., 1979; Wiegand *et al*., 1991), biophysical vegetation characteristics (e.g., leaf area index (LAI)) (Baret and Guyot, 1991; Boissard *et al*., 1993; Holben, 1980), and crop production estimation and yield prediction (Das *et al*., 1993; Domenikiostis *et al*., 2004; Doraiswamy and Cook, 1995; Idso et al., 1980; Labus *et al*., 2002; Manjunath and Potdar 2002; Pinter *et al*., 1981; Shanahan *et al*., 2001; Tucker *et al*., 1980).

One of the first and most widely used vegetation indices is the Normalized Difference Vegetation Index (NDVI) developed by Rouse *et al*. (1973). It was designed to capitalize on the differential response of vegetation in the red and near-infrared (NIR) parts of the spectrum. The formula of the ratio is:

$NDVI = (\rho_{NIR} - \rho_{Red}) / (\rho_{NIR} + \rho_{Red})$

(Where ρ_{NIR} is the near-infrared channel reflectance and ρ_{Red} is the red channel reflectance, respectively.)

Time-series NDVI data have been used widely in studies of land cover characteristics and vegetation phenology because of their correlation with changes in green plant biomass and vegetation cover (Knipling, 1970; Swain and Davis, 1979; Rouse *et al*., 1973 and 1974; 1979; Schneider and McGinnis, 1982; Tarpley, 1984; Holben, 1986). In agro-ecosystems, it is feasible to derive crop type information by analysis of temporal change in NDVI values because different crops exhibit distinct patterns of NDVI variations over a growing season.

3.1.1 Remote Sensing of Agriculture

Since the inception of the Television and Infrared Observation Satellite (TIROS) in 1960, there has been a continual increase in the availability of improved remotely sensed data at various spatial, spectral, and temporal resolutions. Satellite-based remote sensing data have been used extensively for agricultural applications in the Great Plains and other parts of the U.S.A. One of the key application areas involves using satellite data to spectrally characterize crops (e.g., Bauer *et al*., 1980; Daughtry *et al*., 1984; Kastens *et al*., 2005; Lo *et al*., 1986; McAdam, 1997; Odenweller and Johnson, 1984; Price *et al*., 1997; Wardlow *et al*., 2007; Wiegand *et al*., 1990 and 1992). Satellite data have aided in the spectral characterization of major U.S. grain crops for classification and monitoring purposes. Several field-level research campaigns and other studies using multiple dates of MSS data were undertaken in the early 1980's to better understand crop spectral characteristics (e.g., Bauer *et al*., 1980; Daughtry *et al*., 1984; Odenweller and Johnson, 1984; Lo *et al*., 1986). The results from these field-level studies highlighted that temporal information, in the form of phenology-driven spectral changes, was valuable for determining the maturity stage of a crop and distinguishing different crop types. Other field experiments and Landsat-based studies by Wiegand *et al*. (1991); Thenkabail *et al*. (1994); Clevers and van Leeuwen (1996); Marioti *et al.* (1996); and McAdam (1997) have involved the development of vegetation index seasonal profiles that show the progression of crop canopy emergence, maturation, and senescence.

Although Landsat and SPOT remote sensing technology (high spatial resolution (10 to 30-m), multi-spectral imagery) has been employed in the field of agriculture and has demonstrated that crop types can be discriminated based on their spectral profiles using time-series data, it is evident from the literature that only a few of these remote sensing studies have included spectral profile analysis as an initial phase in the overall analysis scheme, particularly as a pre-phase to crop classification and mapping. Furthermore, most of these studies have generally been limited to a relatively localized scale and have not been conducted on a repetitive basis. In addition, the Landsat and SPOT data that have been used are expensive and have limited temporal resolution (16 to 26 days) and areal coverage, thus concealing many details of crop phenology dynamics.

Time-series NDVI data sets from the Advanced Very High Resolution Radiometer (AVHRR) on polar-orbiting weather satellites operated by the National Oceanic and Atmospheric Administration (NOAA) have been used for various agricultural applications that require high temporal resolution because of their daily acquisition capability and bi-weekly composite products. For instance, AVHRR has been used to derive vegetation indices (VIs) useful in depicting the large-scale distribution and phenological changes of vegetation (Gutman, 1991; Lloyd, 1990; Reed *et al.*, 1994). AVHRR-derived VIs have also been used to monitor the temporal response of vegetation to climatic fluctuations in the USA (Di *et al*, 1994; Wang *et al*., 2001; Yang *et al*., 1997). VIs have also been useful for crop condition monitoring and crop yield forecasting and estimation (Allen, *et al*., 2002; Labus *et al*., 2002; etc.) Furthermore, time-series AVHRR NDVI data have been used to produce weekly value-added remote sensing and GIS products that illustrate vegetation/crop condition and progress in the conterminous United States (Lomas *et al*., 2000). The high temporal resolution of the time-series NDVI data in addition to NDVI's correlation with biophysical parameters enables land cover types to be spectrally separated based on their unique phenological behavior throughout the year (Badhwar *et al*., 1982; Thenkabail *et al*., 1994).

Although AVHRR is suitable for regional and global agricultural applications because of its ideal temporal resolution (daily revisit), wide swath (2,700 km), and relative affordability; the major limitations to AVHRR NDVI data are lack of atmospheric correction and coarse spatial resolution (1- to 4-km), which limits the crop specific information that can be extracted from AVHRR data. According to Allen *et al*. (2002), the coarse spatial resolution data cannot routinely provide crop-specific information because of varying crops in the same region, field size limitations, and alternating crop and fallow field patterns. Crop spectral characteristics derived from such coarse spatial resolution do not adequately reflect the progression of crop canopy emergence, maturation and senescence.

Due to the aforementioned reasons, recent regional and national studies have focused on the applications of MODIS 250-m data that has the capability of providing information at an intermediate spatial scale between the high spatial resolution of Landsat and coarse spatial resolution of AVHRR, while still providing daily repeat coverage. More literature is becoming available on crop condition and yield prediction (Doraiswamy *et al*., 2004; Kastens *et al*., 2005; Muratova *et al*., 2005; Reeves *et al*., 2005; Xu *et al*., 2005) and crop classification and mapping (Doraiswamy *et al*., 2003; Price *et al*., 1997; Wardlow and Egbert, 2008; Xiao *et al*., 2006; Xavier *et al*., 2006). However, there is limited literature with a focus on spectral analysis for crop classification (e.g. Wardlow *et al*., 2007), monitoring vegetation dynamics and forage (e.g. Beck *et al*., 2006; Egbert *et al*., 1997; Kawamura *et al*., 2005), and mapping rangeland productivity (e.g. Guo *et al*., 2000a,b; Peterson *et al*., 2002; and Reeves *et al*., 2001). Although a considerable number of research articles on MODIS-based LULC mapping research and applications are beginning to appear in the literature, further work is required to understand spectral patterns of crops in the MODIS 250-m NDVI data as it relates to climatic variations, management practices, and government policies; and as a basis of crop identification and mapping at a national scale. In order to develop agricultural best management practices and for planning purposes at a national level, timely information on crop characteristics at such a geographic scale is needed, and exploratory research in crop profile characterization using MODIS data is essential.

3.1.2 The Moderate Resolution Imaging Spectroradiometer (MODIS)

The MODIS sensor has 36 spectral bands, 7 of which are designed for the study of vegetation and land surfaces: blue (459-479 nm), green (545-565 nm), red (620-670 nm), near infrared (NIR_1: 841-875 nm, NIR_2: 1230-1250 nm) and short wave infrared ($SWIR_1$: 1628-1652 nm, $SWIR_2$: 2105-2155 nm) (Lindsey and Herring, 2002).

MODIS has several attributes, including daily global coverage, moderate spatial resolution (.25 to 1km), rapid availability of data, and cost-free status of data products. Among the key products are MODIS 16-day VI composite products at multiple spatial resolutions (250- and 500-m, and 1-km), comprised of NDVI and enhanced vegetation index (EVI) and the 8-day MODIS Surface Reflectance Product at 250 and 500-m spatial resolutions. The MODIS VI products are designed to provide consistent spatial and temporal comparisons of global vegetation conditions that can be used to monitor photosynthetic activity, while each 8-day composite provides estimates of surface reflectance of the seven spectral bands mentioned above. The MODIS NDVI serves as a 'continuity index' to the existing AVHRR NDVI record (Lindsey and Herring, 2002). EVI was designed to minimize the effects of the atmosphere (e.g., aerosols) and canopy background (e.g., soil and plant litter) that contaminate the NDVI (Huete *et al*., 1997) and enhance the green vegetation signal (Huete *et al*., 2002). The procedure for generating composited, MODIS-based products is the 'constrained view angle' maximum value compositing (CV-MVC), in which the highest NDVI value from a series of multitemporal georeferenced images within a specified range of view angles from nadir is retained for each pixel location in order to minimize cloud and atmosphere contamination, and standardize sun/view angles (Huete *et al.,* 2002 and 1999; van Leeuwen *et al.,* 1999). The MODIS' improved instrumental design contains extensive onboard calibration systems (solar diffuser, solar diffuser stability monitor, and spectro-radiometric calibration assembly) to ensure a calibration accuracy of 2% relative to the sun's radiance (Guether *et al.,* 2002). In addition, the stable and highly precise external orientation knowledge of MODIS' platform and the availability of accurate global ground control point and digital elevation model data sets allows the MODIS data to have a high level of geolocational accuracy (operational goal of 50-m at nadir and 150-m off-nadir) (Wolfe *et al.,* 2002). The MODIS Land Science Team via the NASA Earth Observing System (EOS) Data Gateway provides a suite of these standard products to users free of charge.

3.1.3 A Summary of the Application of MODIS Data for Crop Discrimination in Kansas

Research conducted by Wardlow *et al.* (2007; Wardlow and Egbert (2008) evaluated the general suitability of time-series MODIS (Moderate Resolution Imaging Spectroradiometer) 250-meter EVI (Enhanced Vegetation Index) and NDVI (Normalized Difference Vegetation Index) data for crop-related LULC discrimination in the U.S. Central Great Plains region, and developed and tested a MODIS-based crop mapping protocol.

The data used comprised: a 12-month time-series of 16-day composite MODIS 250-m EVI and NDVI data; annotated aerial photos from the USDA Farm Service Agency (FSA) for 2,800 individual fields in Kansas that were 32.4 ha (80 acres) or larger, containing the field's geographic location, crop type in 2001, acreage, and irrigation/non-irrigation designation; a georeferenced Public Land Survey System (PLSS) coverage; and Landsat Enhanced Thematic Mapper Plus (ETM+) imagery. A field database comprising field site locations, crop types, management practices, and time-series EVI and NDVI data for each crop type, was created using information from annotated aerial photos. According to Wardlow and Egbert (2008), the process involved locating ~2,800 field sites on the MODIS imagery using a georeferenced PLSS coverage and Landsat ETM+ imagery and the selection of a single 250-m pixel located completely within the field's boundary to represent each field. Subsequently, time-series VI date were then extracted for the pixel and visually evaluated to verify that their spectral temporal characteristics were consistent with the crop type reported by the FSA. After verification, the field's time-series VI data and annotated crop information were entered into the database. This process was repeated for each of the ~2,800 field sites and finally a total of 2,179 field sites were retained and aggregated by crop type (alfalfa, winter wheat, corn, sorghum, soybeans) and management practices (double crop, fallow, and irrigation).

Average multi-temporal VI profiles were calculated from the time-series VI data at the state level, and a combination of graphical and statistical analyses were performed. Both MODIS VI data sets were found to have sufficient spatial, spectral, and temporal resolutions to detect unique multi-temporal signatures for each of the region's major crop types and management practices. Each crop's multi-temporal VI signature was consistent with its known general phenological characteristics and most crop classes were spectrally separable at some point during the growing season. The results from this research indicated that MODIS VI data sets are suitable for crop characterization in the U.S. Central Great Plains and offer the potential to map cropping patterns on an annual time step thus providing users with 'current' LU/LC information each year, as well as documenting the inter-annual LULC changes that commonly occur across the Great Plain's agricultural landscape.

Wardlow and Egbert (2008) recommended that further research across the diverse conditions of the U.S. Central Great Plains should be done to build on the Kansas work and develop a regional crop mapping protocol that can be repeated on an annual basis using the time-series MODIS VI data. It was suggested that in developing such a protocol, both the EVI and NDVI data should be tested to further evaluate their applicability for detailed crop mapping. In response to these recommendations, the NDVI data were tested in Nebraska to further evaluate their applicability in other geographic areas of the Central Great Plains.

3.2 RESEARCH OBJECTIVES/QUESTIONS

The objective of this research was to evaluate the applicability of time-series MODIS 250-m NDVI data for crop type spectral profile characterization and discrimination in Nebraska.

Research questions:

3. Do the spectral-temporal profiles of target crops derived from MODIS 250-m NDVI data correspond to the respective crop calendars?
4. Are these spectral-temporal profiles separable enough for crop type identification and, subsequently, mapping?

3.3 STUDY AREA

This study was conducted in the state of Nebraska (Fig. 3.1), which is situated in the heart of the Central Great Plains region of North America. The agricultural sector of Nebraska is intensively developed with approximately 93% of the state's total area (18.4 million ha/45.7 million acres) under cropland and ranches (Nebraska Department of Agriculture, 2007).

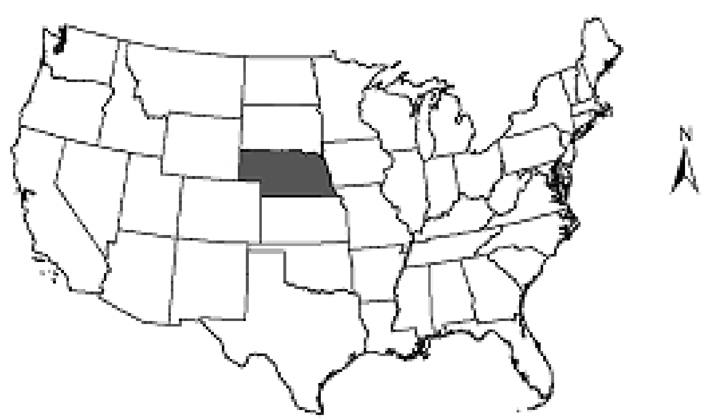


Figure 3.1 The State of Nebraska study area map

The agricultural landscape consists of a mosaic of relatively large fields whose average farm size is about 388 ha (980 acres) with diverse crop types and management practices (USDA, 2007). Some of the major crops grown in Nebraska, which are the subject of this study, are alfalfa (*Medicago sativa*), corn (*Zea mays*), (proso) millet (*Panicum miliaceum L*), sorghum (*Sorghum bicolor*), soybeans (*Glycine max*), sunflowers (*Helianthus annuus*), and winter wheat (*Triticum aestivum*) (USDA, 2007). Alfalfa (USDA, 2000a), corn (USDA, 2006), sunflowers (Thomas *et al*., 2003), and winter wheat (Hein and Kamble, 2003) are grown across the entire state of Nebraska. Although corn, sunflowers, and winter wheat are grown throughout the state, corn is predominantly grown in the eastern third and southern half of the state (USDA, 2006), sunflowers are greatly concentrated in western Nebraska (Thomas *et al*., 2003), while 75% of winter wheat production is in the western half of the state (Hein and Kamble, 2003). Millet production is mainly concentrated in the wheat growing areas of the western half of Nebraska where it is grown in a wheat-millet rotation (Hein and Kamble, 2003), while sorghum is grown primarily in the southern counties of the state (USDA, 2000b). Soybeans are primarily produced in the eastern half of Nebraska with highest production in the eastern third of the state (USDA, 2000c).

Nebraska has a dry, mid-continental climate characterized by cold winters and hot summers, and average annual temperatures that range from about 11^{o} C (52^{o} F) in the southeast to about 9^{o} C (48^{o} F) in the extreme northwest (Britannica Student Encyclopedia, 2007). Variations in the growing season are evident, ranging from 165 days annually in the southwest to 125 days annually in the northwest. The state's total precipitation varies from year to year. However, precipitation averages more than 760 millimeters (30 inches) annually in the southeast to less than 430 millimeters (17 inches) in the western panhandle and the greatest amount of the precipitation falls as rain during the growing season between the months of April and September (Britannica Student Encyclopedia, 2007). Nebraska, therefore, has pronounced climatic gradients: a north-to-south elevation decrease in temperature, an east-to-west decrease in mean precipitation and an east-to-west increase in evapotranspiration, which mainly determine the state's environmental and land use characteristics (Wilhelmi and Wilhite, 2002). Since the above crops have well defined crop calendars, with each crop having a specific planting time range and unique growth patterns (e.g. time of green up, peak greenness, and senescence), the time-series MODIS NDVI profiles should reflect these type of spatio-temporal variations in response to these environmental gradients and associated land management practices.

3.4 DATA AND METHODS

A 12-month time-series of 16-day composite MODIS 250-m NDVI data for field sites of known crop types across Nebraska was analyzed. A total of 1,288 field sites representing each of the eight cover types under investigation were created from the 2006 Cropland Data Layer (CDL) for Nebraska, from the USDA – National Agriculture Statistics Services (NASS) and used as a basis for extracting time-series NDVI values for each crop type. Graphical and statistical analyses were employed to address the research objective. A brief discussion of the data and methods used is provided below.

3.4.1 Time-Series MODIS NDVI Data

The 16-day composite MODIS 250-m NDVI data (MOD13Q1 Collection 004) spanning from January 1 to December 3, 2006 were acquired from the NASA EOS Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/). For each composite period, the MODIS NDVI data were extracted for each tile and the data were mosaicked and reprojected from the Sinusoidal to the Albers Conical Equal Area projection. The reprojected mosaics, 22 in total (composite date of December 19 was missing), were then sequentially stacked by composite period and subset to the state's boundary to produce the final time-series NDVI data set for Nebraska.

3.4.2 Field Site Database

A field site data set for specific crop types was created using the 56-m 2006 Nebraska Crop Data Layer (CDL), produced by USDA-NASS (USDA-NASS, 2007). The 56-m 2006 CDL was derived from ground-based data for crops growing within the state at the time of the June Survey and Indian Remote Sensing (IRS) Resourcesat-1 Advanced Wide Field Sensor (AWiFS) imagery. The classification accuracy was generally between 85% and 95% correct for agricultural-related land cover categories (USDA-NASS, 2007). The producer's accuracy (Table 3.1) for corn, soybeans, and winter wheat was higher than 95%; while alfalfa, millet, and sorghum had accuracy of 79%, 63%, and 52% respectively. Sunflowers had an exceptionally low accuracy of 33%.

Table 3.1 Nebraska 2006 statewide percent correct, commission error and kappa statistics extracted from Nebraska accuracy assessment table (USDA-NASS, 2007). NOTE: User's accuracy and fallow class were not included in the CDL accuracy statistics table.

Crop Cover	**Producer Accuracy %**	**Commission Error**	**Conditional Kappa**
Alfalfa	79.03	11.28	78.12
Corn	97.75	4.55	95.12
Millet	63.28	35.14	62.95
Sorghum	51.59	21.44	51.03
Soybeans	96.73	5.38	95.50
Sunflowers	32.85	32.42	32.75
Winter Wheat	94.93	10.04	94.29

Although issues in the CDL data may exist, possibly arising from the quality of field data and inaccuracies in producing the crop specific digital layers, it was assumed that the 2006 Nebraska CDL product would be suitable for extracting field sites.

The seven crops and fallow land cover type raster layers were separated from the CDL by creating new raster files using a raster calculator in Spatial Analyst, a GIS extension tool. Each separate layer was converted from raster into polygon layer using a GIS raster to polygon conversion tool. Subsequently, the size of each polygon was calculated using pre-logic Visual Basic for Applications (VBA) script code. This was necessary to reduce the number of polygons for each crop layer to a manageable size. Therefore, the average size of the smallest contiguous polygon for the most predominant crops (alfalfa, corn, soybeans, and winter wheat) was set at 56.25 ha (approximately 9 MODIS 250-m pixels), and 37.5ha (approximately 6 MODIS 250-m pixels) for the less predominant crops for which smaller acreages were planted (grain millet, sorghum, and sunflower) and fallow.

A three-composite-date MODIS NDVI raster (e.g., Figure 3.2) in which the crop was expected to have attained considerable growth and maturation was created for each cover type and was used as a background to the crop polygon layers. Table 3.2 lists the composite date range used for each crop. Each crop's polygons that overlapped with the MODIS NDVI raster for the three composite dates were selected. The selected polygons corresponded to the polygon size of above 500 ha for corn and soybeans; above 100 ha for grain millet and winter wheat; above 45 ha, 40 ha, and 30 ha for alfalfa, sorghum, and sunflower, respectively. The MODIS NDVI raster for the three dates of June 29, July 28, and August 29, were used as a background for the fallow polygon layer. The fallow profile in Kansas (Wardlow *et al.,* 2007) was used as guide in the selection of the composite dates. During this time period fallow had the lowest NDVI values in comparison to other cover types. It was assumed that selecting low NDVI values would be ideal in representing fallow sites. The fallow polygons that overlapped with the low MODIS NDVI values were selected. The polygon size of these selected was greater than 85 ha.

Table 3.2 A listing of the composite date range used for each crop for 2006

Crop Type	Composite dates
Alfalfa	April 7, May 9, and May 25
Corn	July 12, July 28, and August 13
Grain Millet	July 12, August 13, and August 29
Sorghum	July 12, August 13, and August 29
Soybeans	July 12, July 28, and August 13
Sunflower	July 12, August 13, and September 14
Winter Wheat	April 7, May 9, and May 25
Fallow	June 26, July 28, and August 29

The centroids for each polygon used in the analysis was computed and examined to determine whether its computed location was accurate. The accuracy was assessed by looking at the geographic location of each centroid to determine whether it appeared near the center of each polygon (Figure 3.2). Centroids that fell just outside or inside the polygon boundaries were manually shifted to the middle of the polygon to ensure that the NDVI values extracted at the centroid locations were away from the polygon edges which would result in the use of NDVI values from mixed pixel cover types. Centroids that fell too far outside the contiguous polygons were removed from the database.

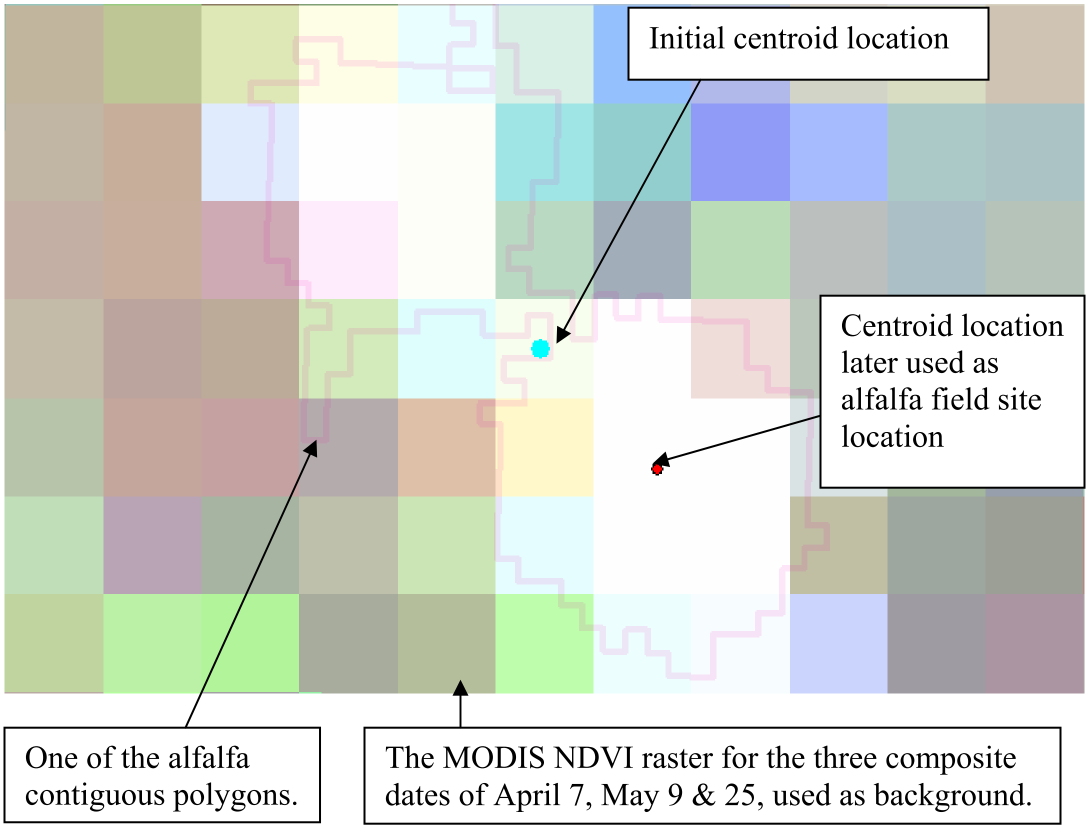


Figure 3.2 An illustration of locational criteria for alfalfa using alfalfa polygon layer and MODIS NDVI raster for the three composite dates in which alfalfa was expected to have attained maximum growth.

The MODIS NDVI grid for the three composite dates for each of the eight crop and fallow layers were used as a background to aid in the selection of a suitable single 250-m pixel to represent each field site. The geographic locations of 1,576 initial centroids (Table 3.3) that meet the locational criteria as demonstrated above were then considered as the locations of each crop's initial field sites.

Table 3.3 Number of land cover contiguous polygons and initial field sites by crop type

Crop Type	Number of polygons after conversion	Minimum average size of polygon (Ha)	Number of Selected Polygons	Polygon average size (Ha)	Initial number of field sites
Alfalfa	31,023	56.25	1158	>45	266
Corn	169,600	56.25	929	>500	380
Grain Millet	13,251	37.5	315	>100	97
Sorghum	7,058	37.5	271	>40	91
Soybeans	95,069	37.5	319	>500	310
Sunflower	1,392	37.5	111	>30	64
Winter Wheat	61,622	56.25	1146	>100	286
Fallow	78,6191	37.5	144	>85	82
Total					1576

3.4.3 Kansas Average NDVI Profiles

A total of 2,800 verified field sites in Kansas were used by Wardlow *et al*. (2007) to extract time-series NDVI values from 2001 MODIS data. Average NDVI profiles were created for the five major crops of alfalfa, corn, grain sorghum, soybeans, and winter wheat. To refine the curves of these crop types, the profiles were visually evaluated to verify that their spectral characteristics were consistent with the general phenology of the crop type reported by the FSA. Each refined curve was considered a standard NDVI profile for the respective crop type in Kansas. Due to the rigorous process of selecting the field sites and curve refinement against field truth, the Kansas profiles are considered to be a valid standard against which Nebraska NDVI curves could be compared. The temporal shifts in a crop's NDVI signature were however observed across Kansas (Wardlow *et al*., 2007). Although noticeable curve time-shifts were anticipated between Kansas and Nebraska because of variation in precipitation and length of crop growing season, it was expected that the general curve patterns would be the same.

3.4.4 Methods

A total of 1,576 initial field sites (Table 3.2) representing all the eight cover types under investigation were used as a basis for extracting time-series NDVI values. The extracted NDVI data from the initial field sites for each crop type (excluding fallow) were subjected to Cluster Analysis (Romesburg, 2004), using *k-means* clustering, as a way of evaluating variability among field sites within each crop type. A *k-means* clustering analysis was chosen because (i) it is an exploratory data analysis tool that is commonly used to discover structures in the data, (ii) the researcher has the advantage of specifying the number of clusters in advance, then calculates how to assign cases to the *k* clusters, and (iii) this type of clustering is much less computer-intensive, therefore it is preferred when the data sets are very large.

Several cluster sizes were tried and in each case profiles were plotted and visually examined. Since some larger cluster sizes did not have members, the maximum cluster size of 10 was assumed adequate. Three cluster data sets of 10, 7 and 3 clusters were generated for crops with a large number of field sites (e.g. alfalfa, corn, soybeans, and winter wheat), while for crops with a relatively small number of field sites (e.g. millet, sorghum, and sunflowers) two data sets of 5 and 3 clusters were generated. After clustering, each cluster's NDVI profiles for each specific crop was created and visually compared to the known MODIS-based profiles of similar crops in Kansas. Due to the fact that data sets with fewer clusters tended to conceal subtle differences among field sites, the 10-cluster data set for crops with large number of field sites and 5-cluster data set for crop with a relatively small number of field sites were deemed adequate in revealing the field sites' variability. Cluster profiles that were consistent with the spectral-temporal profiles of a similar crop in Kansas were aggregated to represent crop-specific, state-level time-series NDVI profiles for Nebraska. When the field sites in each cluster were mapped, the pattern did not show any regionalization. Using this refining process, cluster profiles that were outliers for sites atypical of Kansas's crop phenology were identified and removed. Profiles of millet and sunflower were not available for Kansas. Millet cluster profiles were evaluated independently and a profile that was consistent with the general seasonal pattern of an annual crop growth cycle was selected. A typical sunflower profile was selected after sunflower cluster profiles were compared to the Landsat-based profiles demonstrated in Odenweller and Johnson (1984). A full discussion on the refinement of the field sample data set is given in the previous chapter.

As an example, Figure 3.3 shows that in Kansas, the alfalfa profile (Wardlow *et al*., 2007) is characterized by a steep ascending phase because of the rapid increase in NDVI during the early spring, multiple 'growth and cut' cycles, and a gently descending phase. The profiles of clusters 5, 8, 9, and 10 in the Nebraska data set, although relatively higher, displayed a general form that was consistent with the profile of alfalfa in Kansas. Each cluster profile showed minor variations in the timing of green up span of the growing period, and in the 'growth and cut' cycles. The 'growth and cut' cycles were not synchronous but more pronounced at different time periods because of variations in the number, timing, and quantity of foliage cuttings per year. The descending phase for clusters 5 and 9 occurred relatively earlier than the other clusters.

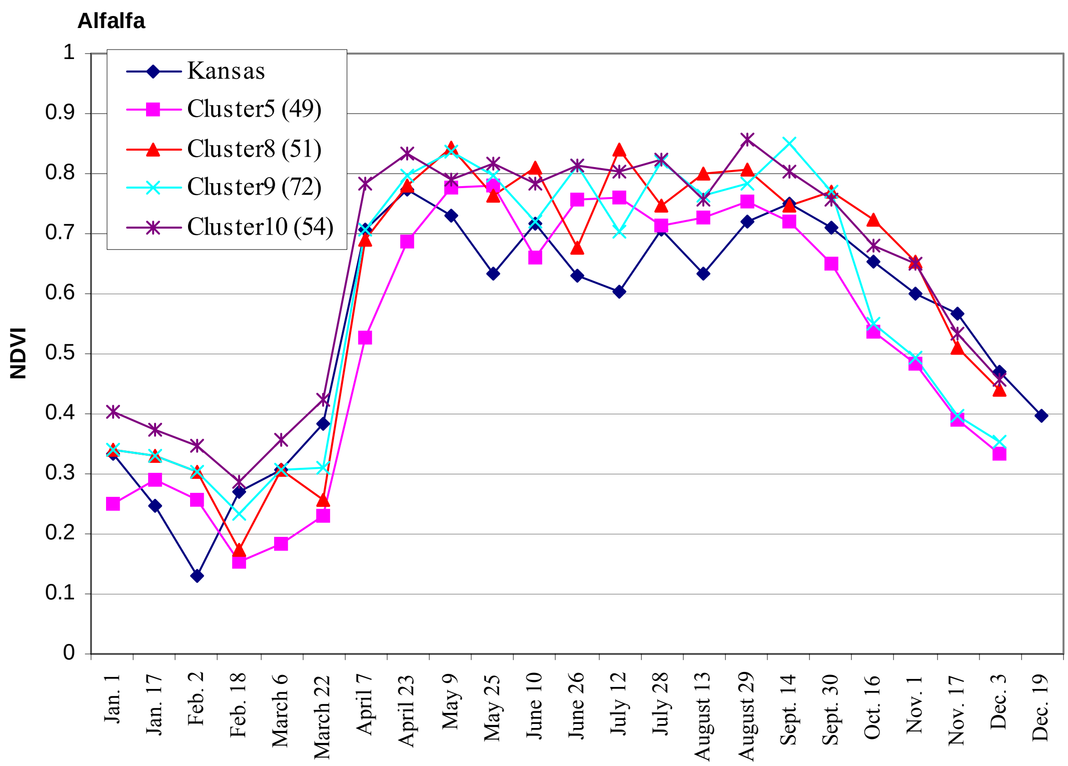


Figure 3.3. Alfalfa. Time-series average NDVI profiles of Kansas and retained Nebraska clusters. Nebraska clusters have numbers of selected field sites in parentheses

Since the NDVI profiles of clusters 5, 8, 9, and 10 were consistent with the Kansas alfalfa profile, their field sites totaling 226 constituted the alfalfa reference data set for Nebraska.

The profiles of clusters 1, 2, 3, 4, and 7 were not consistent with the alfalfa profile in Kansas (Fig. 3.4). Clusters 1 and 7 had a shorter growing period, while clusters 2 and 3 displayed what is apparently a double cropping pattern.

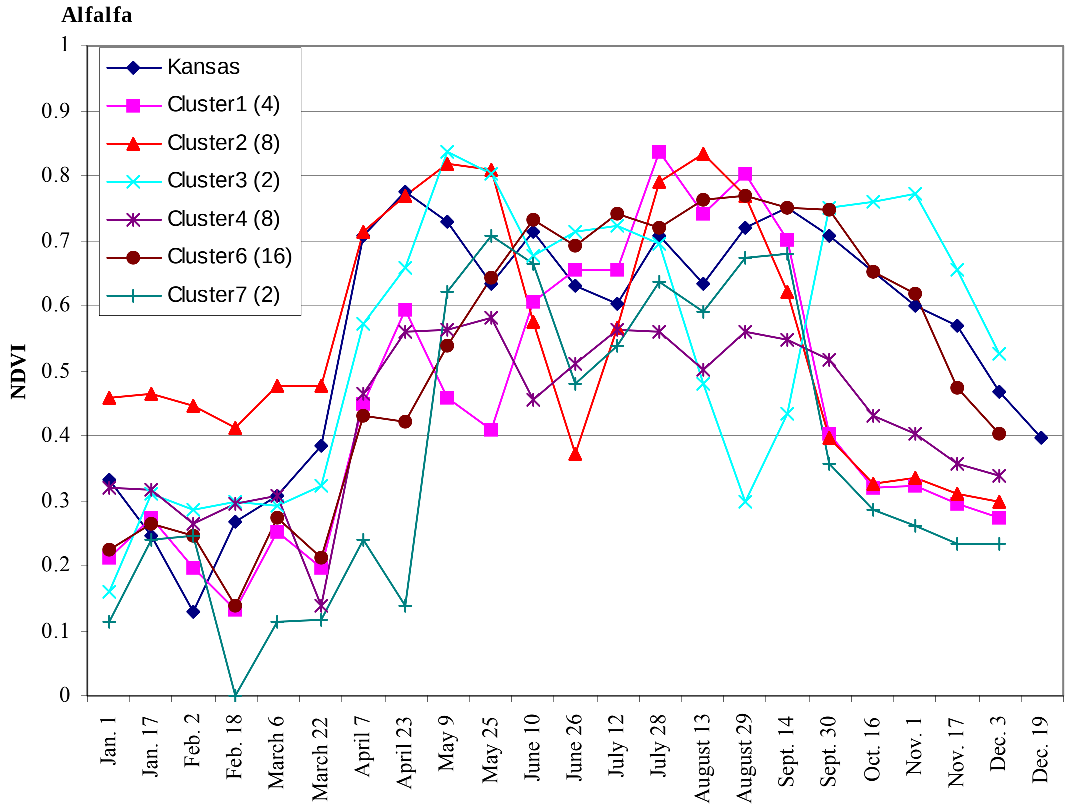


Figure 3.4 Alfalfa. Time-series average NDVI profiles of Kansas and rejected Nebraska clusters. Nebraska clusters have numbers of rejected field sites in parentheses.

The descending phase of clusters 1, 2, and 7 was steeper than for the other clusters with pronounced depressions possibly due to extended harvesting period. Although clusters 4 and 6 were similar to alfalfa, cluster 4 had a generally low profile possibly because of less vigorous growth or drought stress. Cluster 6 indicates that possibly there was drought stress during the early phase of the crop's growth and its general pattern did not display pronounced multiple 'growth and cut' cycles. Because of the cluster profiles' inconsistent growth patterns, their field sites, 40 in total, were removed from the alfalfa reference data set.

Cluster profiles of winter wheat, corn, sorghum, soybeans, sunflower, and millet were evaluated in a similar fashion and cluster profiles consistent with the phenological patterns of known crops were retained. After completing this field site refinement process, there were 1,288 sites retained for further analysis. These sites hereafter will be referred to as 'final' field sites (Table 3.4, Fig. 3.5).

Table 3.4 Number of 'initial' and 'final' field sites by crop type

Crop Type	**Initial field sites**	**Final field sites**
Alfalfa	266	226
Corn	380	370
Grain Millet	97	19
Sorghum	91	83
Soybeans	310	303
Sunflower	64	20
Winter Wheat	286	185
Fallow	82	82
Total	1576	1288

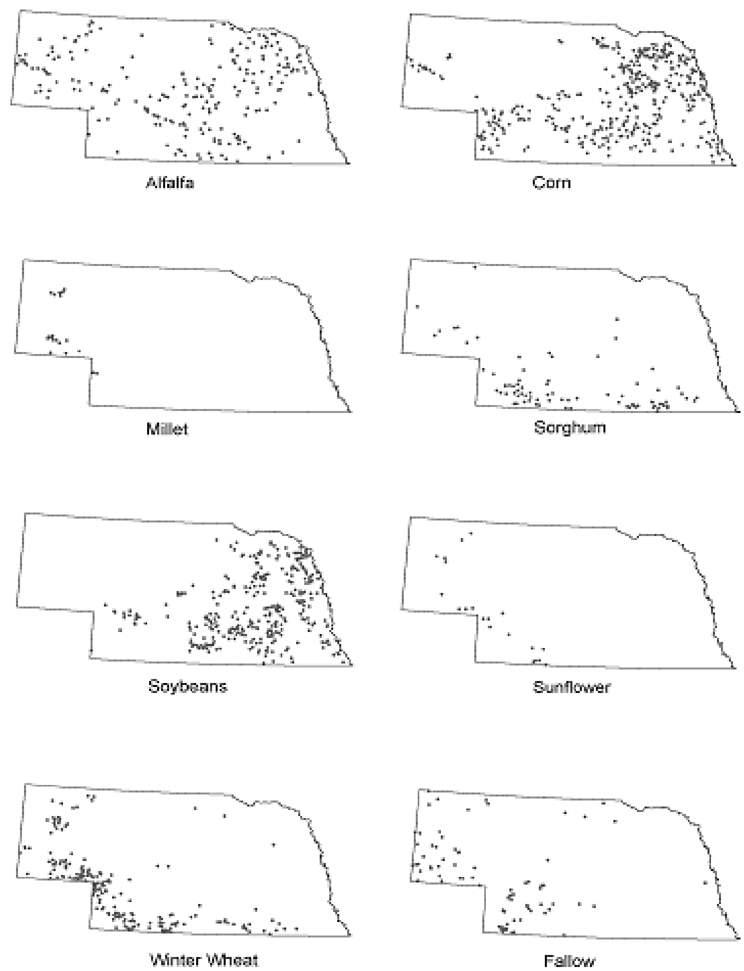


Figure 3.5 Retained field site locations by crop type

The methodology employed in this study to evaluate the applicability of the time-series MODIS 250-m NDVI data for crop discrimination involved both graphical and statistical analyses. First, the time-series NDVI values from the initial field sites were aggregated by crop type, and, using average NDVI values, state-level multi-temporal NDVI profiles were plotted for each crop type and fallow land cover category. After clustering, average, state-level multi-temporal NDVI profiles were calculated for all crop clusters. Clusters whose profiles were typical of their respective crop calendars were aggregated to represent crop-specific state-level time-series NDVI profiles. The overall crop and crop-cluster NDVI profiles were then visually assessed and compared to their respective crop calendars to ascertain if each crop's unique phenological pattern was detected in the time-series NDVI data and that the temporal-spectral responses corresponded to their respective crop calendars.

Second, class separability between specific crop types in the time-series NDVI data was investigated graphically by plotting the mean, crop-specific NDVI time-series along with their period-specific, one standard deviation error bars; and numerically using the Jeffries-Matusita (JM) distance statistic (Richard and Jia, 1999). JM distance has been affirmed in previous research work to be an effective measure of evaluating class separability (van Niel *et al*., 2005; Wardlow *et al*., 2007). Under normality assumptions, the JM distance between classes *i* and *j* is given by

$$JM_{ij} = 2(1 - e^{-a})$$

where $$a = \tfrac{1}{8}(\mu_i - \mu_j)^T \left(\frac{\Sigma_i + \Sigma_j}{2} \right)^{-1} (\mu_i - \mu_j) + \tfrac{1}{2} \ln \left(\frac{\left| \frac{\Sigma_i + \Sigma_j}{2} \right|}{|\Sigma_i|^{1/2} |\Sigma_j|^{1/2}} \right)$$

In this study, μ_i and μ_j are the class-specific mean NDVI values at a particular time period (or, more generally, vectors of mean values for a span of time periods), and $\sum_i$ and $\sum_j$ are unbiased estimates for the class-specific variance values at the time period (or, more generally, covariance matrices for a span of time periods). JM distance values range between 0 and 2. A maximum JM distance of 2 between two classes means that the class-specific distributions are perfectly distinguishable from each other, while a minimum JM distance of 0 indicates that two class-specific distributions are indistinguishable from each other.

3.5 RESULTS and DISCUSSION

3.5.1 Time-series NDVI Profiles and Crop Phenological Characteristics

The state average time-series NDVI profiles of crop types were visually assessed and compared to each class's phenological pattern to determine if the unique spectral-temporal responses correspond to their respective crop phenological characteristics (crop calendars). Also in this section and the subsequent one (3.5.2), an attempt was made where possible to compare the results with those obtained in a similar study in Kansas (Wardlow, 2005; Wardlow *et al*., 2007).

General Crop Types

The time-series NDVI profiles for each crop type presented in Figure 3.6 show graphically that each crop type had a unique and well-defined profile. Each crop's unique profile results from differences in timing of green up, peak greenness, and senescence. Distinct spectral-temporal differences were discernible between NDVI profiles of alfalfa and winter wheat, and summer crops (corn, millet, sorghum, soybeans, and sunflowers). The timing of green up for alfalfa and winter wheat occurred in early spring (*i.e.* late March), much earlier than that of summer crops. The peak NDVI values (*i.e.,* peak greenness) for alfalfa and winter wheat were attained in mid-spring (*i.e.,* late April and early May) in contrast to summer crops whose peak NDVI values were attained in mid-summer (*i.e.,* early July and late August). The specific spectral-temporal differences were elucidated during the comparison of each crop's NDVI cluster profiles and the profile of aggregated clusters (*i.e.*, state average), and crop calendar (phenology).

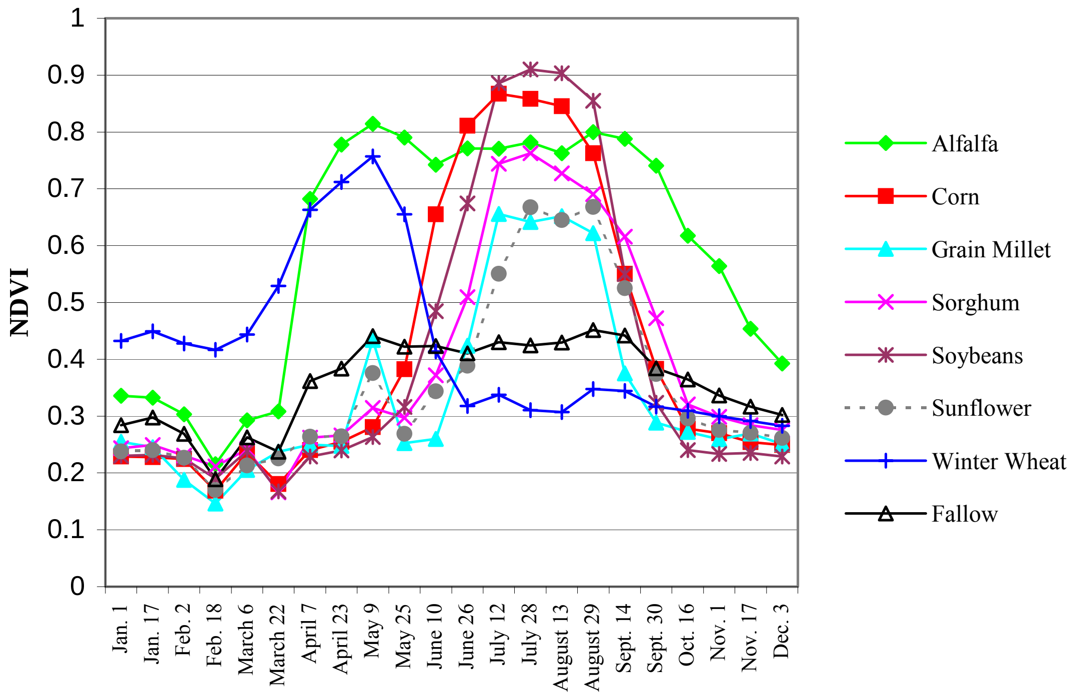


Fig.3.6 Time-series NDVI profiles (state average) of major crop types in Nebraska.

Alfalfa

Alfalfa (USDA, 2000a) is a perennial legume crop usually seeded in the fall (August 1 to September 15) or spring (March 15 to April 30) for dry land production. Under irrigation, alfalfa can be seeded any time from April through September. It breaks winter dormancy and begins photosynthetic activity/growth in early spring. When the alfalfa foliage is fully grown, it may receive three to four cuttings per growing season in Nebraska. Alfalfa is grown in pure stands, as well as alfalfa-grass mixtures.

The crop's phenological characteristics and the 'growth and cut' cycles were visible in the time-series NDVI data (Figures 3.7), as illustrated by the profile of the state average.

The early spring green up corresponded to a rapid NDVI increase (from 0.3 to >0.8) between the composite periods of March 22 and May 9. However, the typical 'growth and cut' cycles were somewhat subdued, because the 'growth and cut' cycles for the four alfalfa clusters making up the state average profile were not synchronous. Although the general growth pattern of alfalfa at the state level was similar in both Nebraska and Kansas, the NDVI profile during the year 2001 in Kansas revealed three much more pronounced 'growth and cut' cycles.

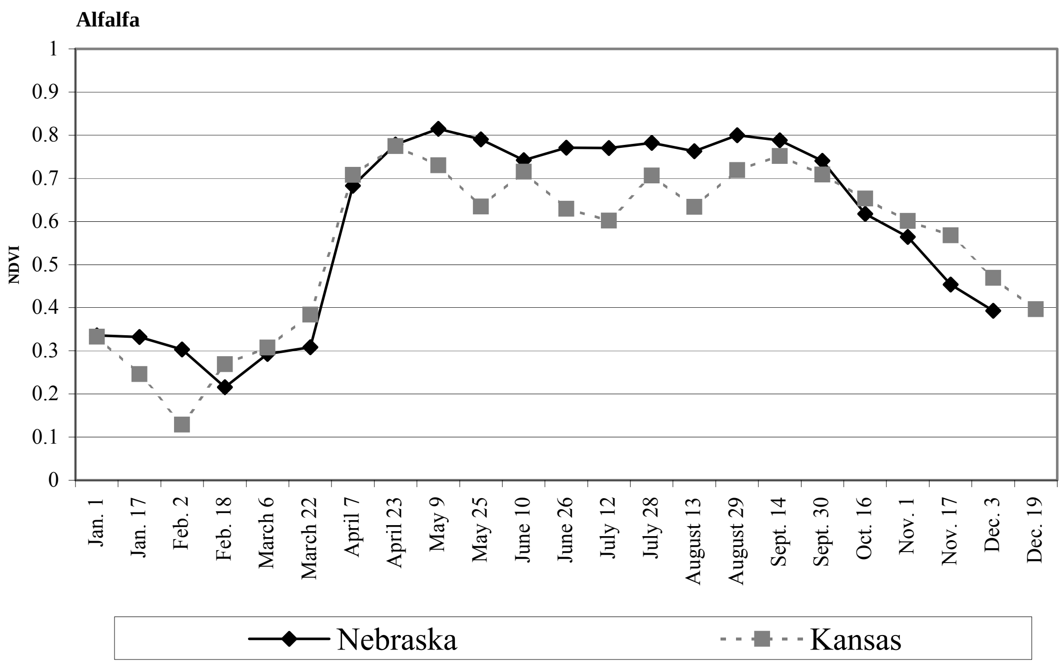


Fig 3.7 Time-series NDVI profile (state average) of alfalfa in Nebraska and Kansas.

Winter Wheat

In Nebraska, winter wheat is planted and emerges in the fall (usually in September or October) when soil moisture is optimum for germination and plant emergence (Hein and

Kamble, 2003). The crop goes into dormancy over the winter and breaks dormancy and begins to grow in the spring (March). The plant's vegetation growth and maturity are characterized by head formation, flowering, and kernel development, followed by senescence. Harvesting of winter wheat begins in the east in late-June or early-July and mid- to late-July in the west (Hein and Kamble, 2003).

The state average winter wheat NDVI profile characteristics (Figures 3.8) reflect the crop's distinctive crop calendar discussed above and are in general agreement with the timing of the vegetation/growth, maturation/ripening, and harvesting of the crop in Nebraska.

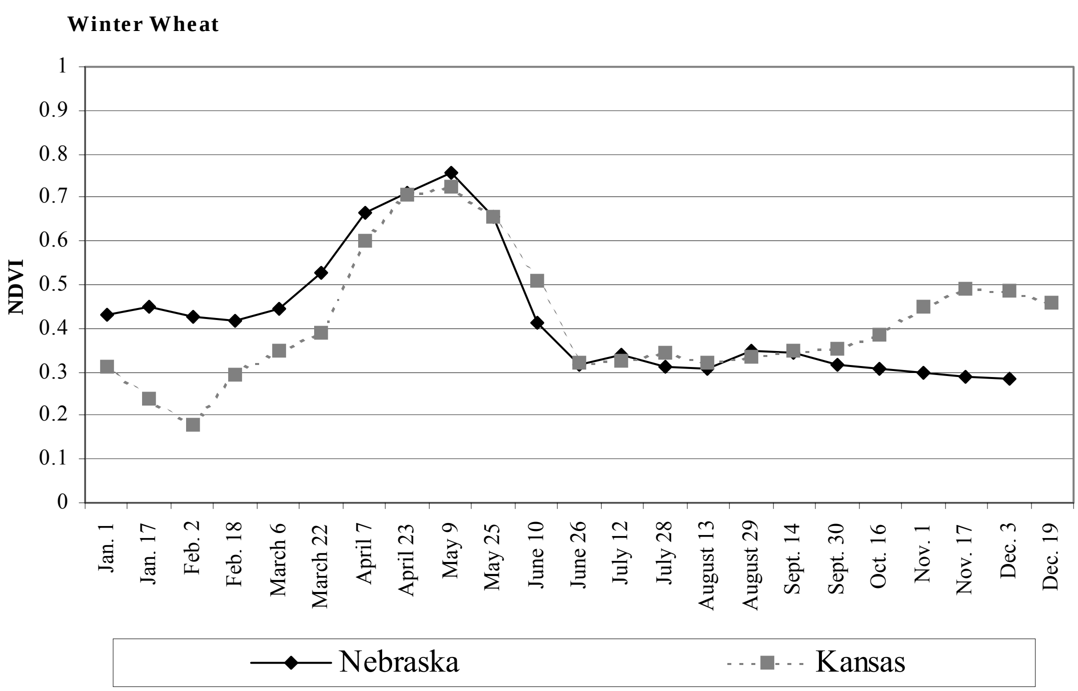


Fig 3.8 Time-series NDVI profile (state average) of winter wheat in Nebraska and Kansas.

The low NDVI values (0.41 – 0.44) during the period between January through mid-March, are indicative of the dormancy stage. The break in dormancy was represented by the initial NDVI increase between March 22 and April 7 composite periods. The peak NDVI value of 0.75 was attained in early May and the decrease in NDVI values (senescence) began by the composite date of May 25 with a low value of 0.31 being reached by the composite date of June 26. These profile characteristics were similar to the winter wheat NDVI characteristics in Kansas.

Specific Summer Crops – state average NDVI profiles

Crops that grow in the summer are often grouped together for analysis and modeling purposes as ‘summer crops’. Among such summer crops are corn, millet, sorghum, soybeans, and sunflowers. Despite these crops having similar crop calendars, their respective state average NDVI profiles (Figure 3.9) revealed variations that were consistent with subtle differences in their respective crop calendars. The influence of the planting dates was evident from the phased green up patterns. The timing and value of the peak NDVI was also variable among the summer crops. The peak growing season differences may be due to differences in the length of each crop’s growing season, canopy structure, and plant physiology. In general there was agreement between growth patterns of summer crops in Nebraska and Kansas, with the exception of corn that had a relatively higher peak NDVI value and apparently longer growing span in Nebraska.

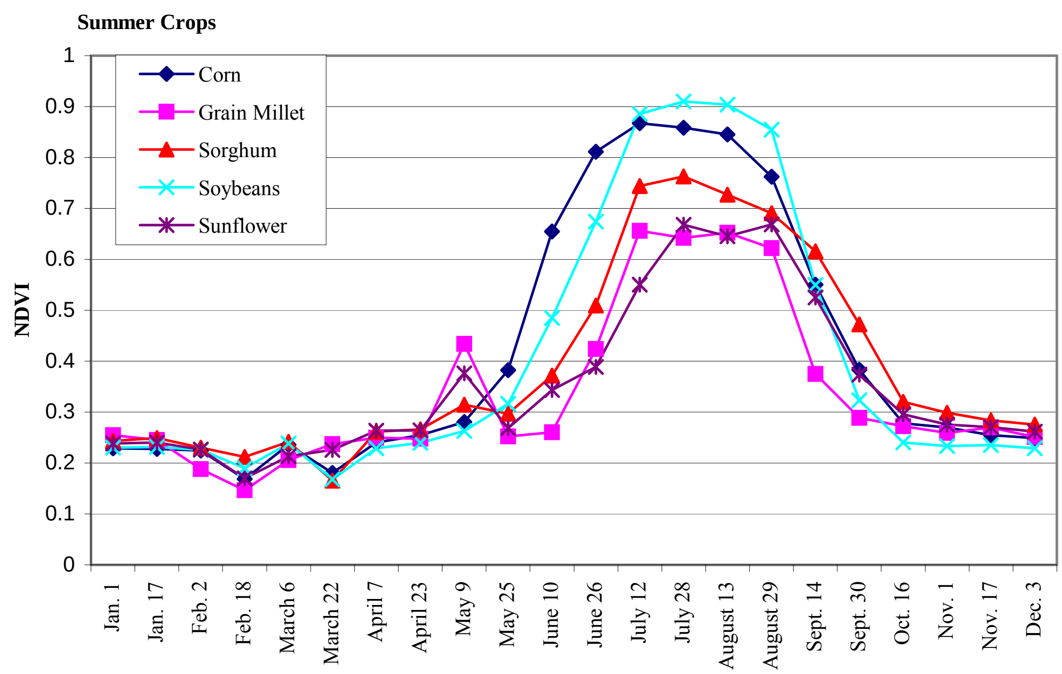


Fig 3.9 Time-series NDVI profile (state average) of summer crops in Nebraska.

Corn

The planting of corn usually begins in the last week of April and ends by the first week of June, with the bulk of the acreage planted in the first and last weeks of May (USDA, 1997). Corn experiences a rapid development of vegetation material followed by flowering and grain filling (McWilliams et al., 1999) and harvesting is carried out between late-September to early-November (UDSA, 1997).

Corn's NDVI profile (figure 3.10) shows low NDVI values of <0.38 before the composite date of May 25 due to a lack of green cover during field preparation and planting. The NDVI values increase rapidly from 0.38 to 0.81 between composite dates of May 25 and June 26, the time period during which corn was expected to experience a rapid installation of vegetative material. The maximum peak NDVI value of 0.87 was reached by July 12 and was consistently above 0.80 until after August 13, as the crop attained full vegetative growth, followed by flowering and grain filling. After August 29, the NDVI values started decreasing, reaching a relatively low value of 0.38 by September 30, resulting from crop senescence and harvesting.

Millet

Proso millet (*Panicum miliaceum L*) is a small grain cereal generally grown as a late-seeded short season summer crop. The crop is usually planted between mid-May and late June and takes between 60 and 90 days from planting to harvest (McDonald *et al*., 2003). During the growth phase the plant produces few tillers (Baltensperger, 2002) and has a relatively open canopy structure (University of Nebraska Cooperative Extension). The crop is harvested usually during September, when the seeds in the upper half of the panicle are mature (McDonald *et al*., 2003)

The NDVI profile for millet (figure 3.10) depicts a sharp ascent, and a relatively lower and narrower profile. The crop peaked during the July 12 composite period with NDVI value of 0.65 and the values remained relatively high until after the composite period of August 29 (<70 days), possibly due to the plant's open canopy structure and a short growing season. From August 29 to September 29, the NDVI values had dropped from 0.62 to 0.37 as a result of senescence setting in and crop harvesting. There is a pre-growing season spike by May 9 possibly as a result of spring weed growth, particularly common in winter wheat-millet crop rotation system.

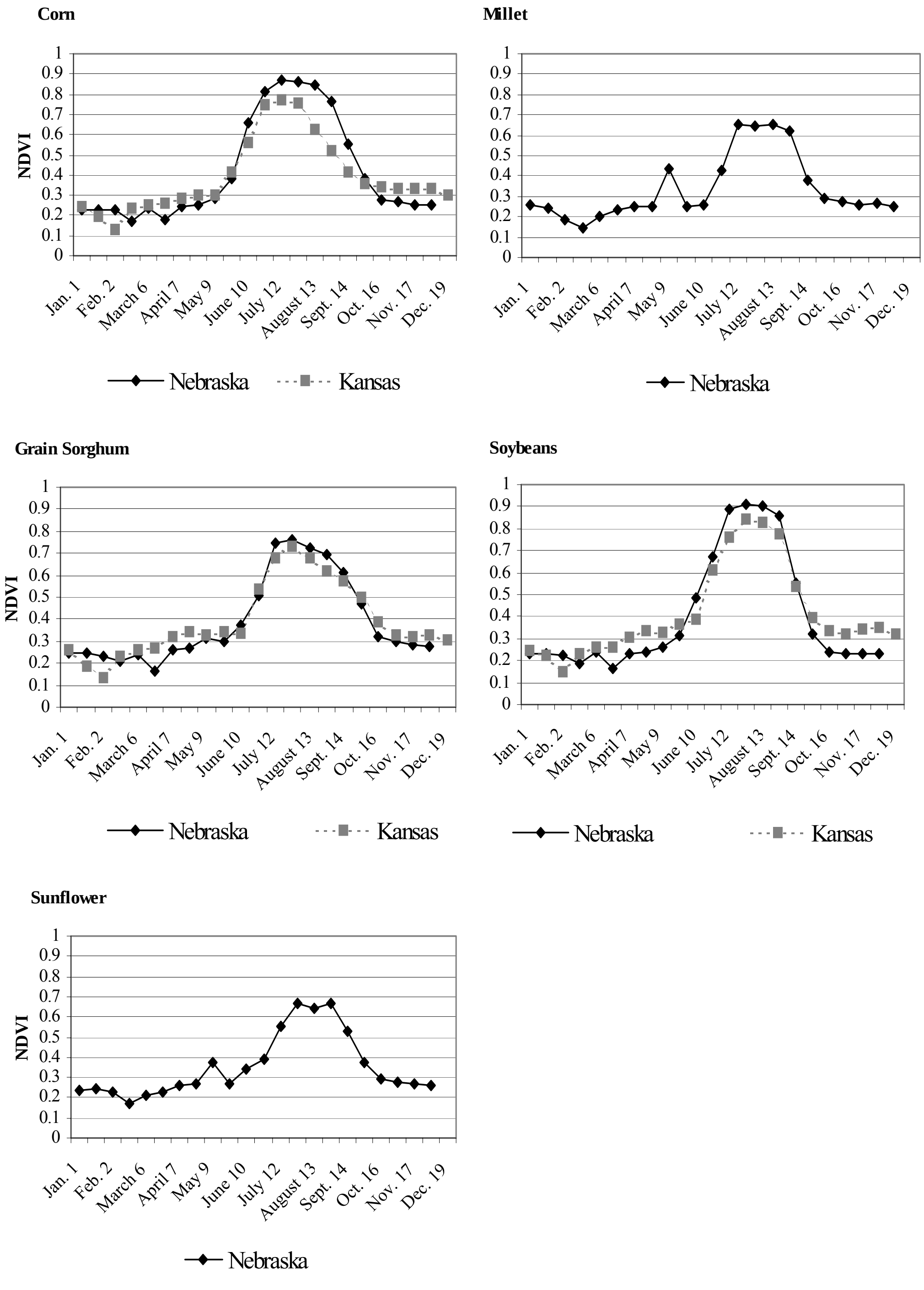


Figure 3.10 Summer crops. Time-series NDVI profiles in Nebraska and Kansas. No millet and sunflower curves were available from Kansas for comparison.

Sorghum

Sorghum planting begins in early May and ends in late June (USDA, 1997), usually after other row crops have been planted. The crop experiences rapid growth and nutrient uptake and at boot stage (50 days from emergence) all leaves are fully expanded (Vanderlip, 1993). During the maturity and senescence phases, sorghum's leaves are relatively green and often remain partially green at harvest (Vanderlip *et al*., 1998). Harvesting of sorghum begins in late September and ends in late November, with October being the most active month (USDA, 1997).

Grain sorghum's NDVI profile (figure 3.10) depicts a relatively sharper ascending phase, a peak greenness value of 0.78 by July 28, and a gradual descending trend during the maturity and senescence phases, consistent with the above noted senescence behavior of sorghum. Sorghum maintained an intermediate NDVI value well into September, which reflects the partial green cover of the crop at time of harvest. The NDVI value decreased from 0.61 by September 14, to 0.47 and 0.032 by September 30 and October 16, respectively, during the crop-harvesting period.

Soybeans

Soybean planting takes place in mid May to early June and harvesting is from late September to late October (USDA, 1997). Emergence normally takes 5 to 10 days after planting, followed by rapid vegetative and reproductive phases (McWilliams *et al*., 2004). When the crop attains full maturity, the green foliage changes color as it dries up and rapid leaf drop occurs after desiccation (Rogers, 1997), and subsequently the crop is harvested beginning around September 19.

The soybean NDVI profile (figure 3.10) has a sharper steeper ascending and descending pattern than most crops, and has higher maximum amplitude than other summer crops, reaching a peak NDVI value of .91 during the July 28 composite period. The higher peak greenness occurs well into the crop's development cycle because of its continued vegetative growth until flowering. The steep drop after August 29, to an NDVI value of 032 by September 30, seems to be in line with the crop's phenological characteristics of green foliage drying and harvesting during the maturity and senescence phases.

Sunflower

Sunflower planting takes place in late-May to mid-June (Thomas *et al*., 2003). After emergence, the plant grows rapidly, taking approximately 120 days to reach maturity. The sunflower plant usually has only a single, hair-covered stem that is heavily branched with small leaves. Crop harvesting starts in September after the backs of the sunflower heads are yellow or yellowish brown (Schneiter and Miller, 1981).

Gentle ascending and descending phases during the crop's growing season characterize the NDVI profile for sunflower (figure 3.10). The crop peaked during the July 28 composite period with an NDVI value of 0.67. However, because of the crop's smaller leaves and perhaps also because the flowers are note comprised of green photosynthetic material, the profile depicts relatively lower values (0.67 to 0.65) until after August 13. The harvesting that takes place in September, accounts for the decrease in the NDVI values from 0.52 by September 14 to a low value of 0.37 by September 30.

Fallow

Fallowing is a common farming technique that is used to conserve soil moisture in drier parts of the U.S. Central Great Plains. In Nebraska, fallowing is practiced in the western part of the state where much of winter wheat is grown in a wheat-fallow rotation. Although fallow is not a crop, it was considered for analysis because it is a common land cover type in Nebraska. The fallow NDVI profile (Figure 3.11) shows relatively lower NDVI values (<0.45) during the growing season, resulting from crop stubble and soil. This fallow profile was relatively higher in comparison with the Kansas one whose NDVI value was <0.3 during the growing season. The Kansas profile exhibited a winter wheat crop in the fall, whereas the Nebraska sites remained unplanted/idle.

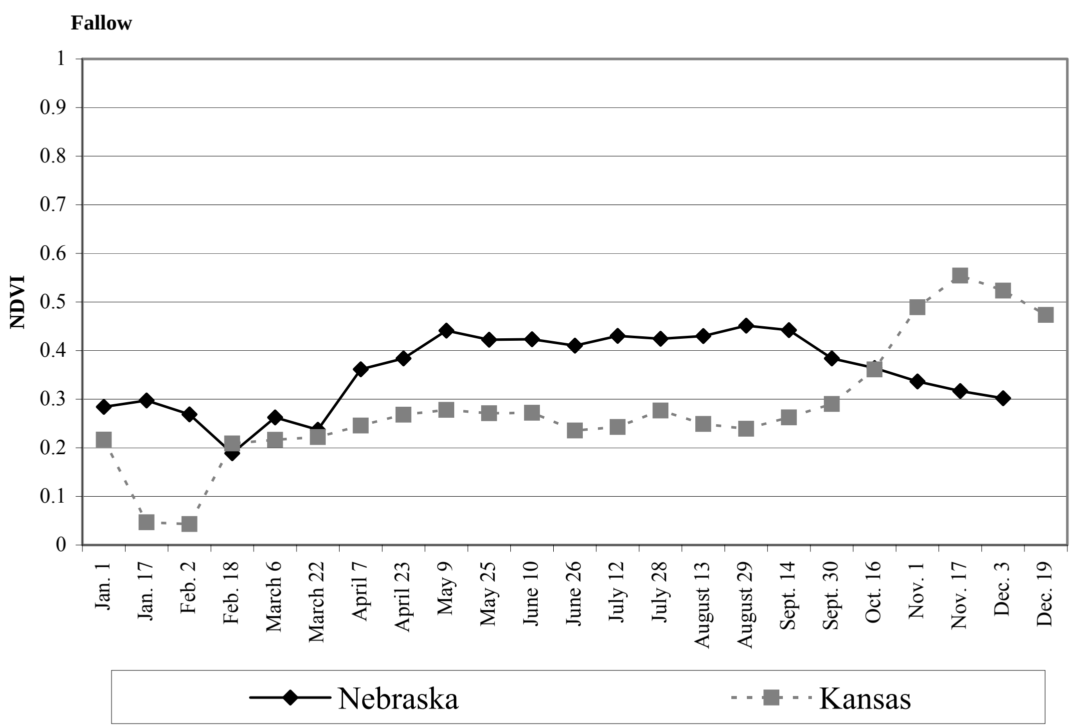


Fig 3.11 Time-series NDVI profile (state average) of fallow in Nebraska and Kansas.

3.5.2 Inter-Class Comparison of Crop NDVI Profiles

Visual comparisons of the average NDVI profiles in figure 3.6 show that the crop types were separable at different times of the growing season based on their phenology-driven spectral-temporal differences. However, a crop may have intra-class variability across a large geographic area due to variation in environmental conditions and management practices as has been shown previously in varying NDVI cluster profiles for a single crop. In this section, the assessment of separability between specific crop types in the time-series NDVI data was done by visual comparison of graphs created using time-series of period-specific mean and ± 1standard deviations of crop-specific NDVI values (NDVI range), and numerically using the JM distance statistic. In both cases class state averages were used.

Visual Comparison

A total of 28 graphs of crop and fallow pairs were visually evaluated to determine the extent of crop separability. Due to the large number of graphs that were available for evaluation, only 5 (*i.e.,* alfalfa and winter wheat, alfalfa and corn, corn and millet, millet and sunflower, and corn and fallow) have been presented. A visual comparison of all the graphs revealed that alfalfa & winter wheat, alfalfa & summer crops, and winter wheat and summer crops were clearly visually separable. However, pairs of specific summer crop types were not easily distinguishable from each other. These results were similar to the Kansas study results (Wardlow *et al*., 2007; Wardlow and Egbert, 2008).

Figure 3.12 revealed that during the spring when both winter wheat and alfalfa begin to green up and attain peak greenness, the two crops are nearly inseparable. However, they become separable by June 10, when winter wheat begins senescence, while the perennial alfalfa continues to experience ‘growth and cut’ cycles. This clear separability continues until November 17, when senescence and the onset of winter dormancy for alfalfa set in.

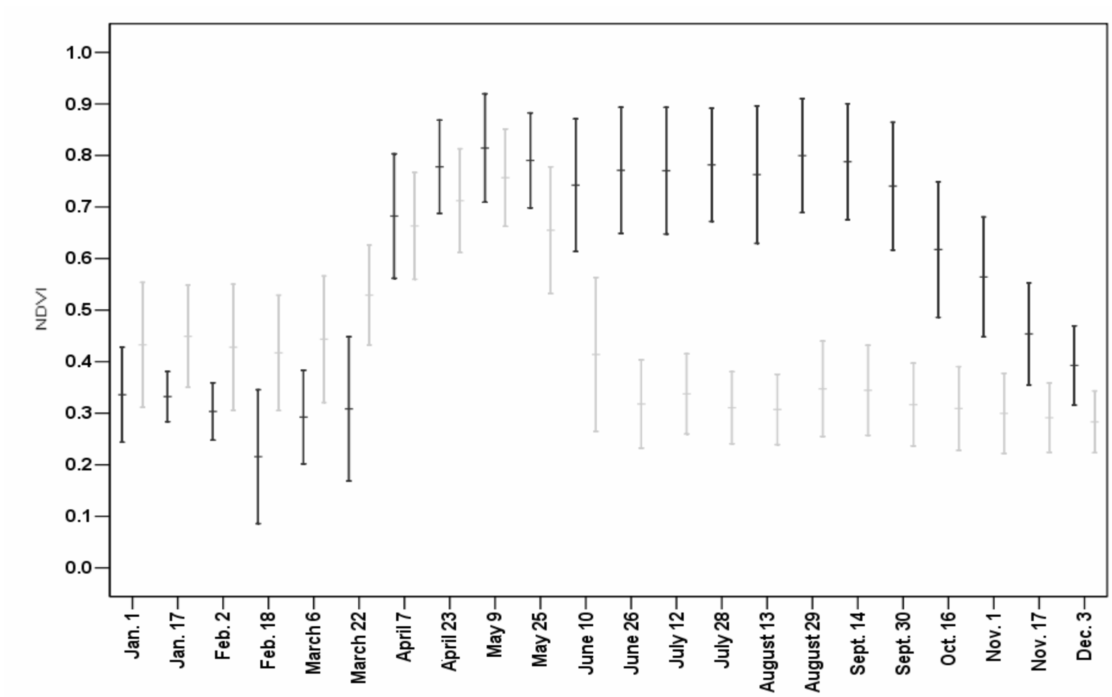


Figure 3.12 State-level average NDVI values (± 1 standard deviation) for alfalfa (black) and winter wheat (gray).

Alfalfa and summer crops are distinctively separable from April 7 to June 26, the period during which alfalfa reaches full growth and summer crops just begin to grow after planting and emergence. For example, the alfalfa and corn NDVI ranges (Figure 3.13) were easily separable between April 7 and May 25. In the case of alfalfa and sorghum, and alfalfa and soybeans, the period of separability extends to June 10, while for alfalfa and millet, and alfalfa and sunflower the separability extends to June 26. From late-June to September the

NDVI ranges for alfalfa and all summer crops overlap, making the separation extremely difficult during this time period when summer crops' NDVI signals are very high.

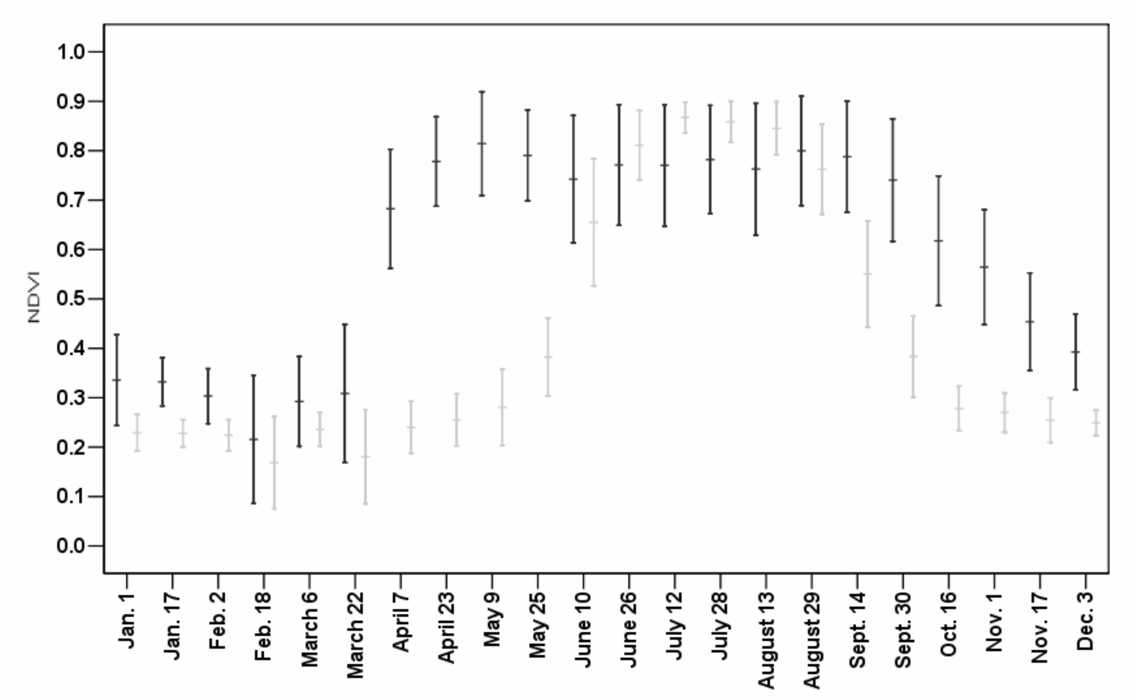


Figure 3.13 State-level average NDVI values (± 1 standard deviation) for alfalfa (black) and corn (gray).

Winter wheat and summer crops were separable in spring when wheat was greening and maturing and summer crops were either not yet planted or just emerging. The separability was also clear from June 10 onwards because their growth cycles occur at different times of the year. Winter wheat is grown early, senesces and is harvested by June, whereas the summer crops rapidly grow and attain peak greenness during the peak of summer.

It was more difficult to separate summer crops from each other due to their similar crop calendars. The separation between corn and the other four summer crops was very clear during the green up and senescence phases of the growing season because corn planting, emergence, and growth take place somewhat earlier than other crops. Summer crop pairs with a relatively longer separation time period were corn/millet (Figure 3.14) and corn/sunflowers, spanning from May 25 to August 13. Similarly, millet/soybeans and soybeans/sunflower were separable over a longer period between June 10 to August 29 and June 10 to August 13, respectively.

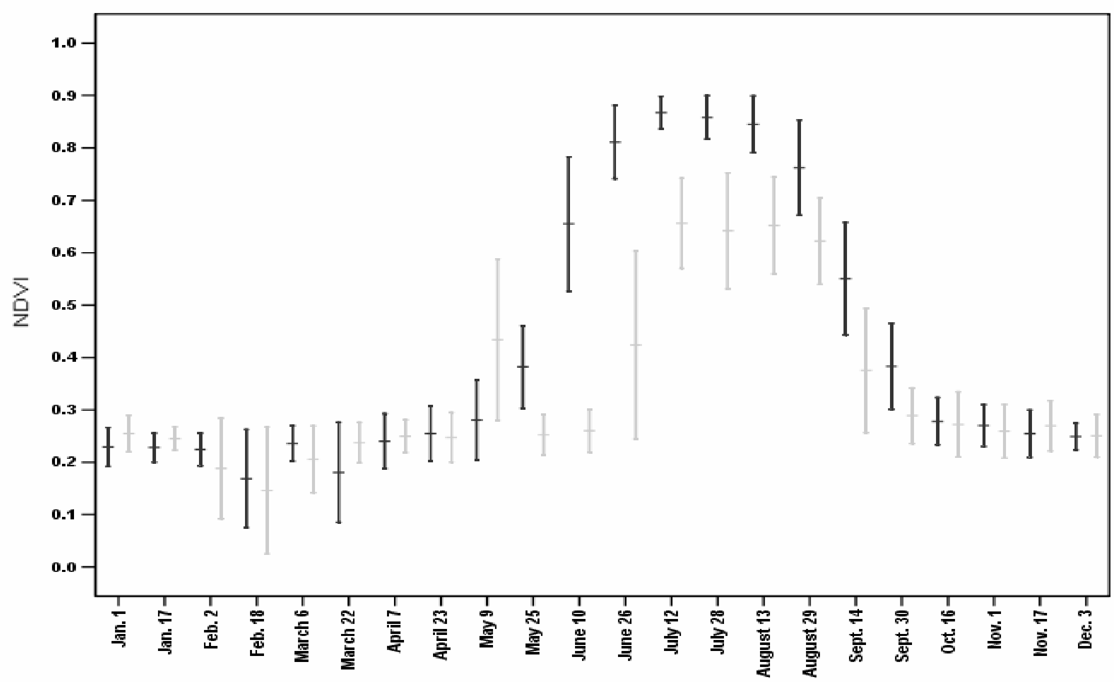


Figure 3.14 State-level average NDVI values (± 1 standard deviation) for corn (black) and millet (gray).

In the case of the corn/soybeans (July 28 – August 13), corn/sorghum (June 10 – June 26), and millet/sorghum (September 14 – 30) crop pairs, each had a very short separation time period. The growth cycles of corn and soybeans were very similar, with corn reaching senescence earlier, in late August. The soybeans/sorghum crop pair was only separable by August 13. However, the millet/sunflower (Figure 3.15) and sorghum/sunflower pairs did not appear to have a clear separation period during their growing cycles.

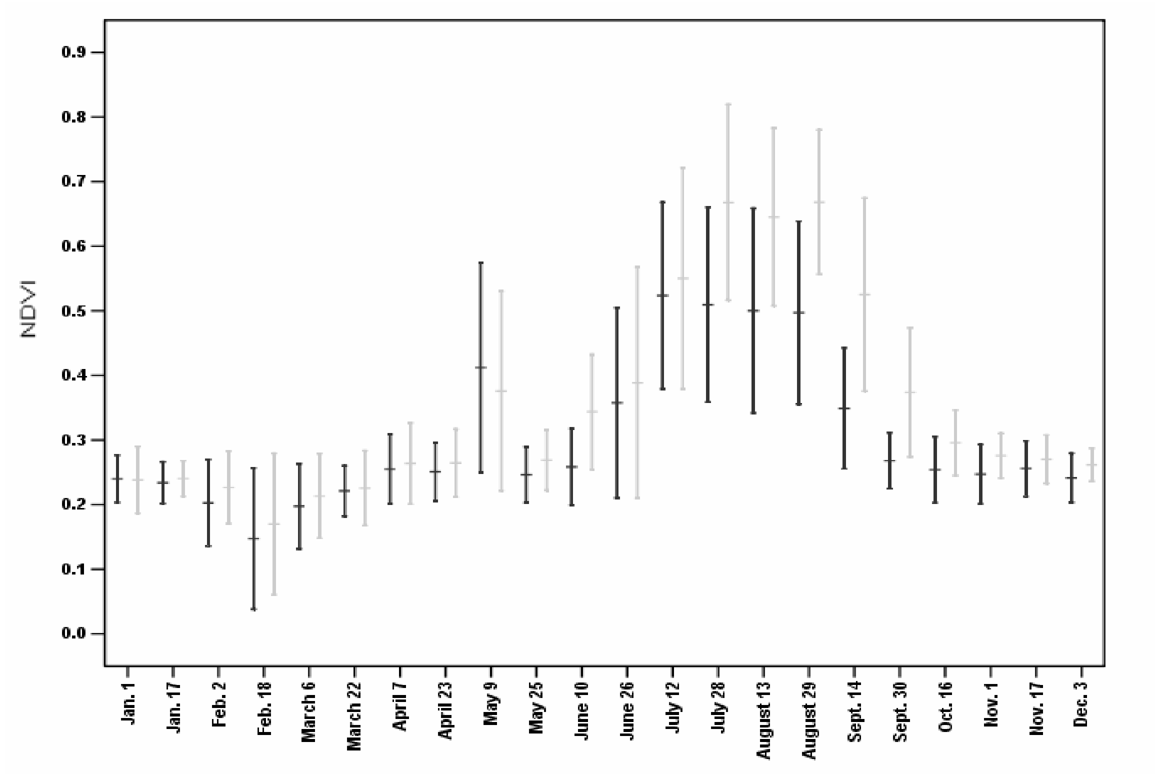


Figure 3.15 State-level average NDVI values (± 1 standard deviation) for millet (black) and sunflower (gray).

Fallow was clearly separable from all crops during their respective growing season as illustrated by the example in Figure 3.16. This was expected because the fallow NDVI profile (Figure 3.9) clearly showed low NDVI values of less than 0.45 during the crop-growing season. Although the separation of grain millet and sorghum from fallow was not very distinct during the most part of the growing season, they were separable in mid-late summer. There was a relatively low separability with millet in early April and late May, while sorghum was separable from fallow in late July.

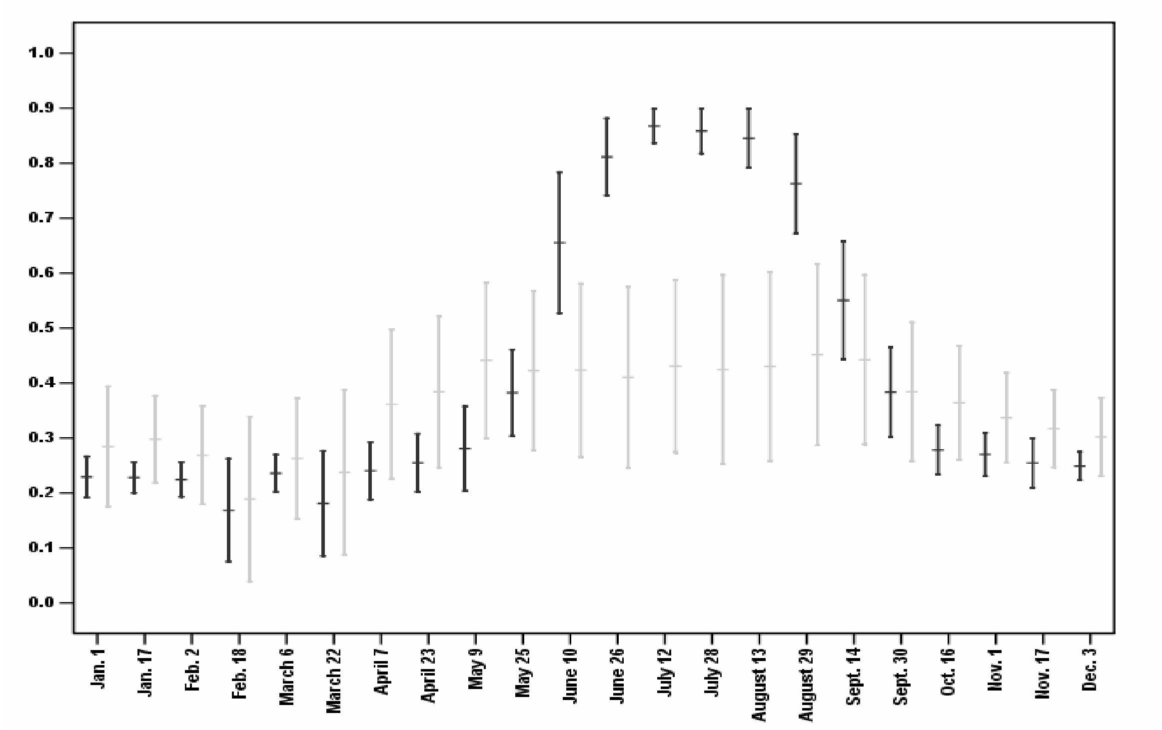
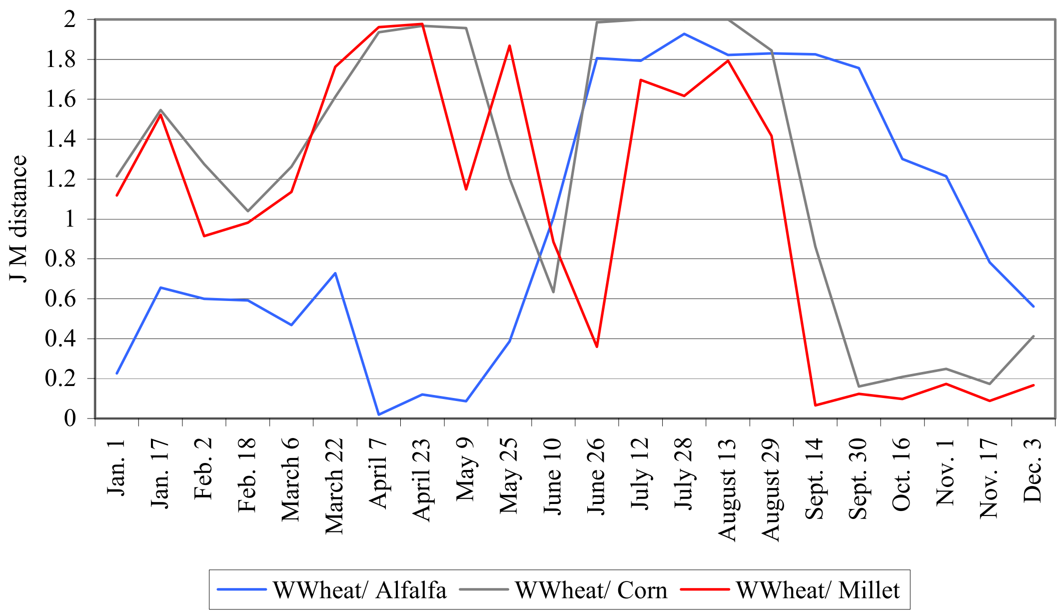


Figure 3.16 State-level average NDVI values (± 1 standard deviation) for corn (black) and fallow (gray).

JM Distance Statistic

After the JM distance statistic was calculated for the 28 crop and fallow pairs, the pair-wise JM distances were plotted in graph form (Figures 3.17, 3.18, 3.19, and 3.20) thus enabling the display of more crop pairs in one graph. Figure 3.17 (a) revealed that, as expected, winter wheat and alfalfa had very high separability (JM distances > 1.8) between the composite periods from June 10 to November 1, because of the presence of alfalfa in the field and the senescence and harvest of winter wheat starting in early June. The separation diminishes from mid-November onwards and continues during winter as both crops, which are seeded in the fall, emerge and go into dormancy over the winter. During spring period, the two crops are not very separable. Winter wheat and summer crops had two distinctively continuous composite periods in the spring (March to May) and the summer (June to August) during which separability values were high, with several JM distances from these time spans greater than 1.8 [Figure 3.17 (a) and (b)]. This trend could be attributed to the differences in the growth cycles of winter wheat (peak greenness and senescence in the reference composite periods respectively) and summer crops (green up and peak greenness respectively). For instance, winter wheat and corn were highly separable between March 22 (JM=1.61) to May 9 (JM=1.96) and June 26 (JM=1.99) to August 29 (JM=1.85), the time periods during which the two crops were in different phases of the growing season. However, the two crops were not separable in early June.

(a)



(b)

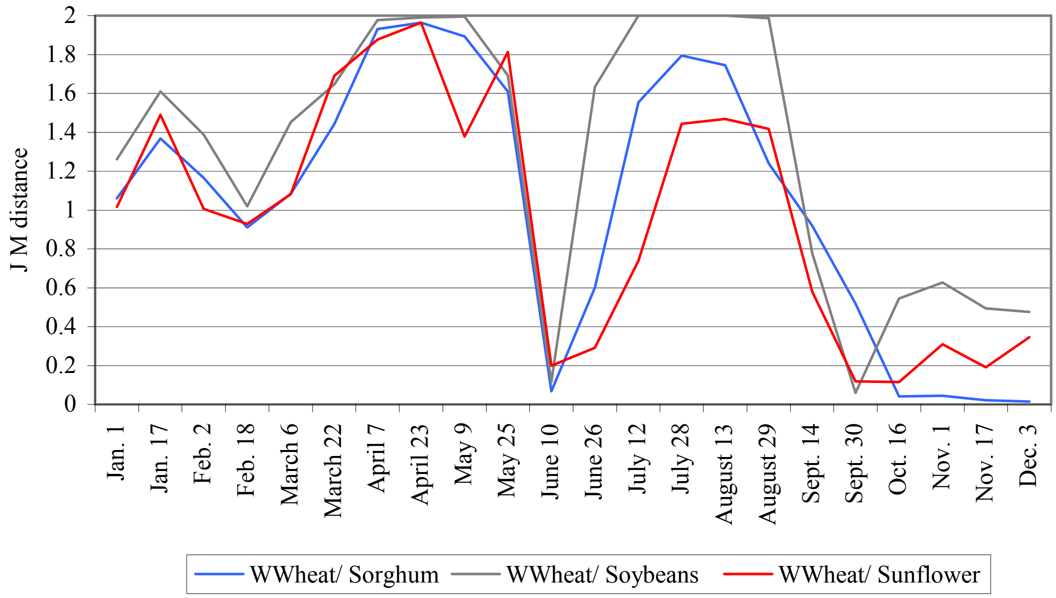
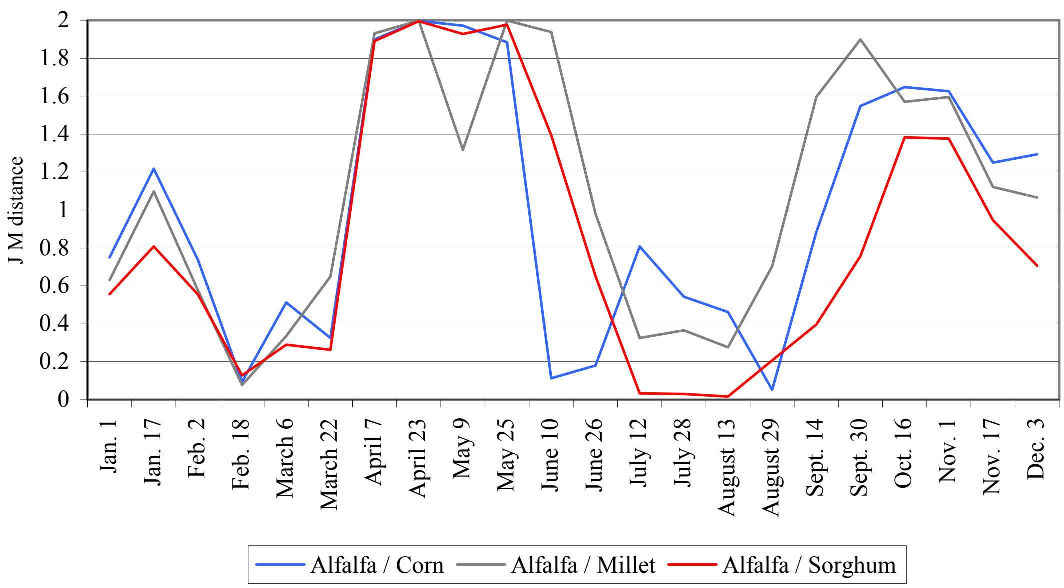


Figure 3.17 The JM distance values observed when comparing field site mean NDVI values for winter wheat to the other six crops.

The separation trend between alfalfa and summer crops is similar to that of winter wheat and summer crops in the spring. Alfalfa and summer crops had very high to perfect separability (JM distance values near 2.0) (Figure 3.18) during the spring (April to May/early June) when alfalfa was in growth and most summer crops had yet to be planted. There was a small reduction in separability by the composite period of May 9 as pre-season weeds in millet and sunflower fields greened up. The second phase of separability was during the fall (September- November) following the senescence and harvest of the summer crops and the continued growth of alfalfa. During June through August composite periods, there was a decreased level of separability as alfalfa and summer crops all reached full growth with soybeans having the highest peak. The JM values slightly increased in late-July and August between alfalfa and both corn and soybeans because the alfalfa cutting (Figure 3.7) coincided with the peak growth for corn and soybeans (Figure 3.9), as evidenced from the relatively low NDVI values of 0.78 and 0.76 for alfalfa, in comparison to 0.88 and 0.90 for both corn and soybeans during this time

period.

(a)



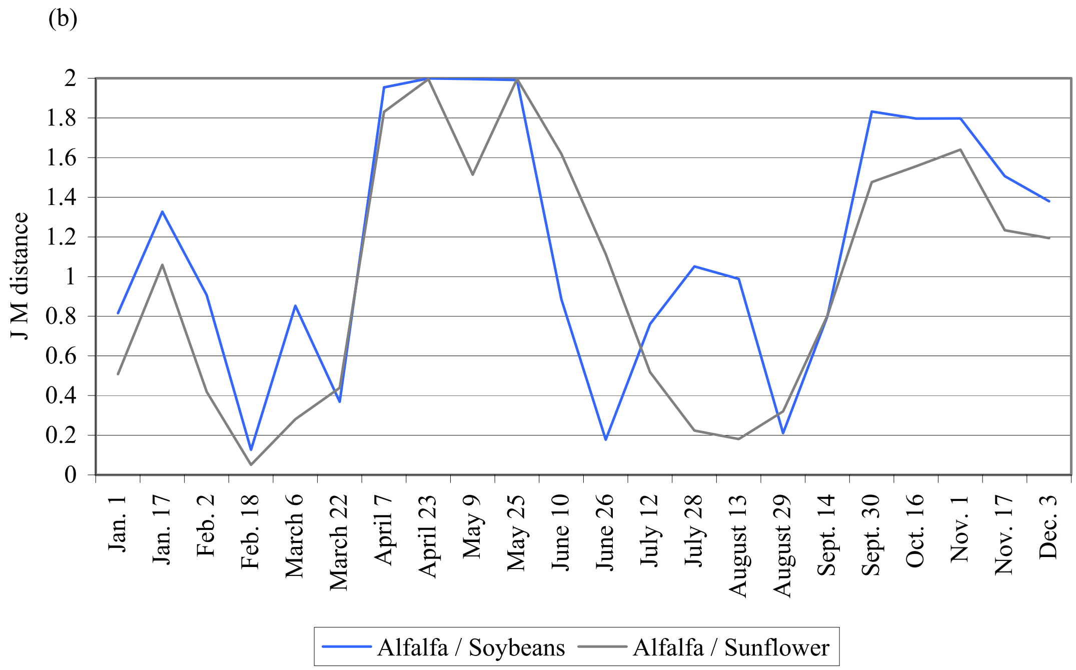
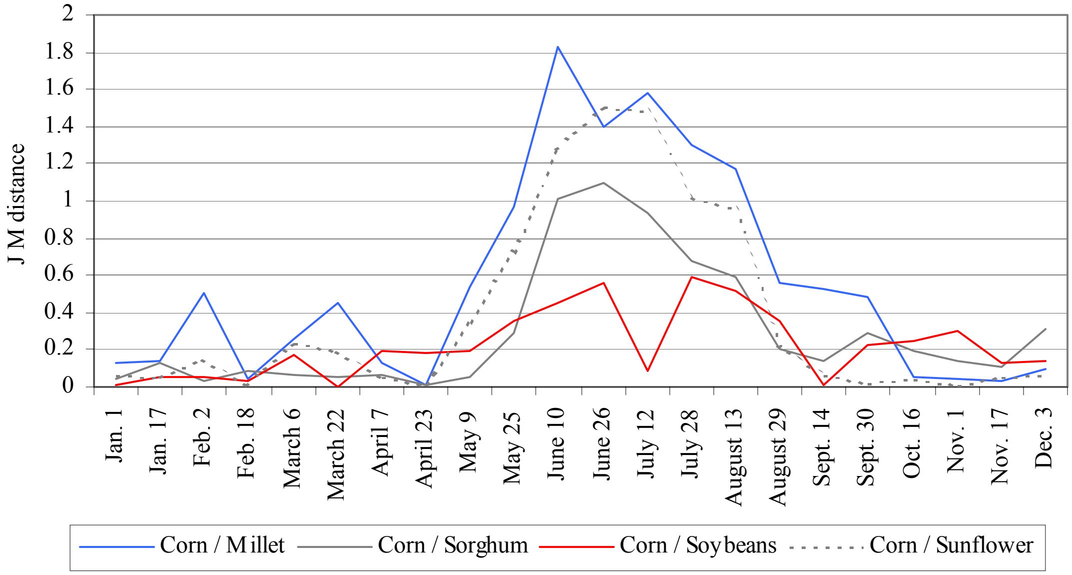


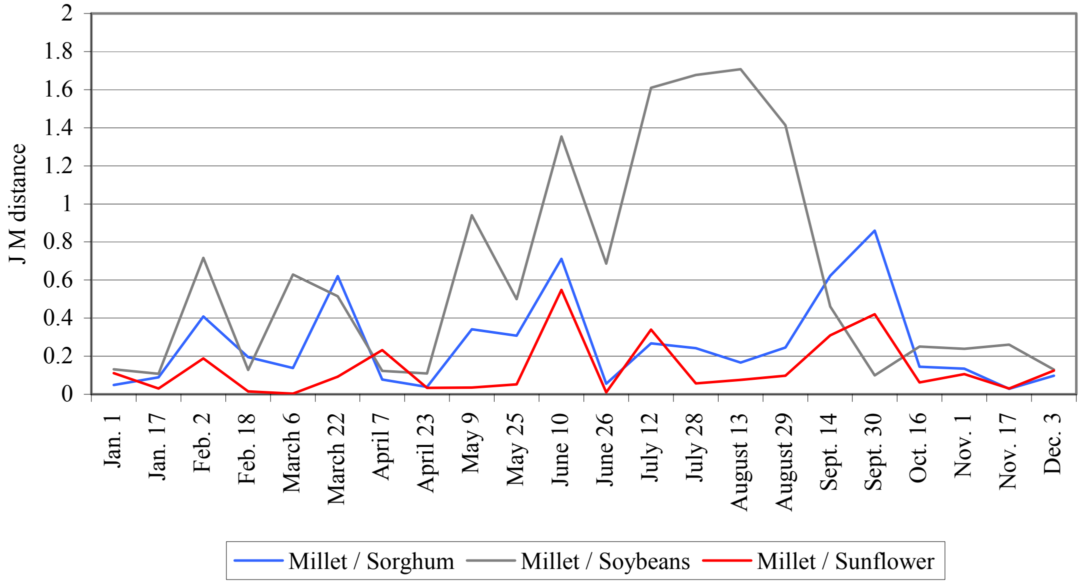
Figure 3.18 The JM distance values observed when comparing field site mean NDVI values for alfalfa to other five summer crops.

Figure 3.19 (a), (b), and (c) shows that six summer crop-pairs had JM distances of greater than 1.0 during the greenup and senescence phases. Corn had high separability from millet during the period from June 10 to August 13, sunflower from June 10 to July 28, and sorghum from June 10 to June 26; with the greatest values of 1.82, 1.51, and 1.10 respectively in the June composite periods for these three crops. The greatest separability between millet and soybeans was 1.71 between the composite dates of July 12 and August 29. Soybeans were separable from sorghum and sunflowers from mid/late July to August 13 with the greatest separability values of 1.13 (August 13) and 1.47 (July) respectively. However, relatively low separability, generally below 0.6, was observed between corn and soybeans, millet and sunflowers, and sorghum and sunflowers throughout the growing season.

(a)



(b)



(c)

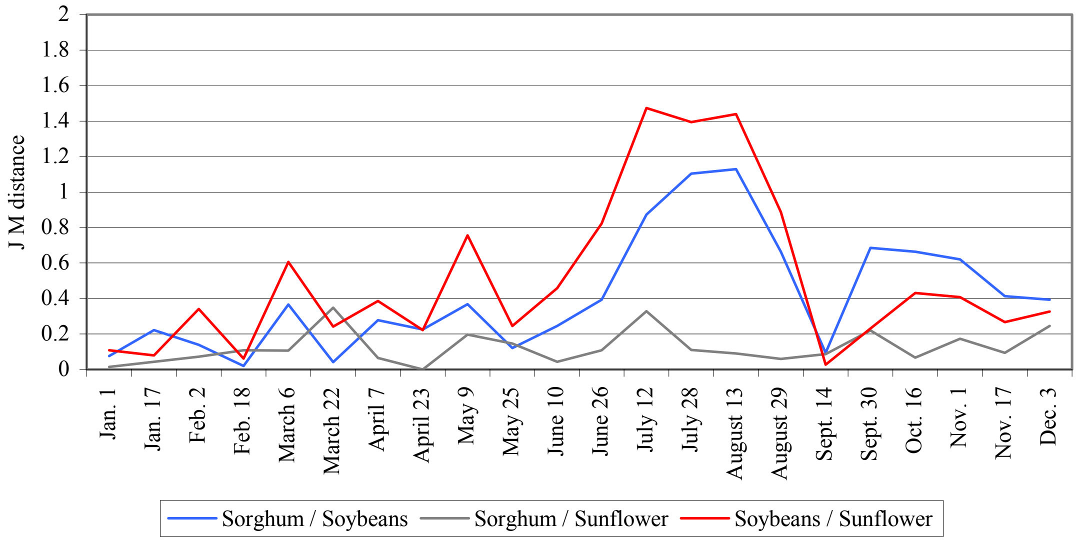
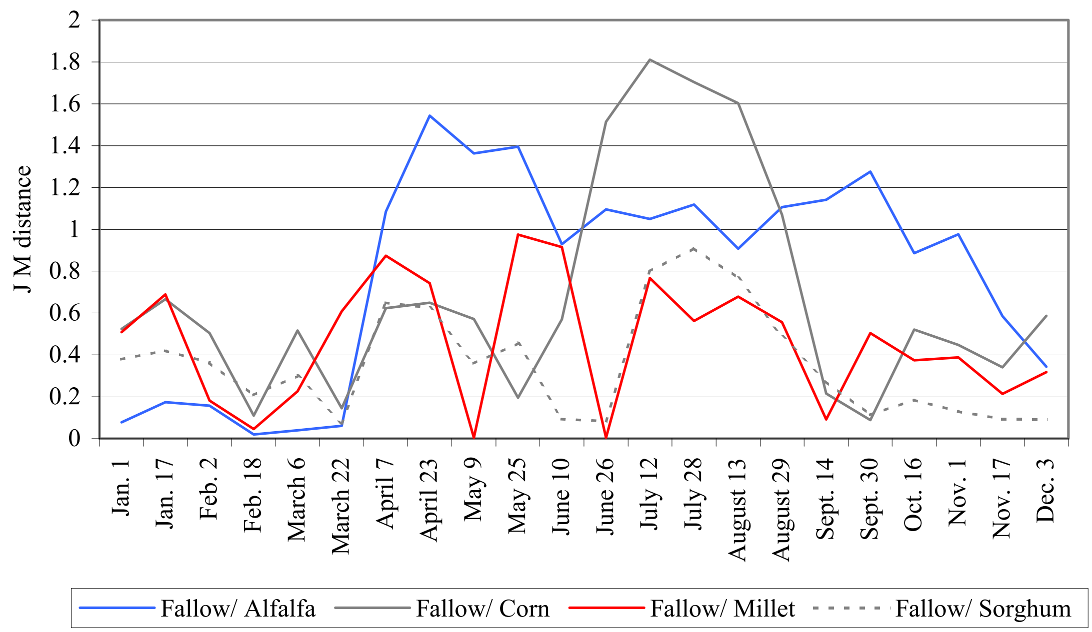


Figure 3.19 The JM distance values observed when comparing field site mean NDVI values for all pairs of five summer crops.

Figure 3.20 (a) and (b) reveals that during the spring, fallow had high separability from alfalfa (JM>1.2) and winter wheat (JM>1.6), and in the summer from soybeans (JM>1.8) and corn (JM>1.6) as these crops' high NDVI response from their full growth canopies were well above that of the weeds and stubble common to fallow fields. The other fallow/crop pairs had very low values (<1.0), making the distinction between them extremely difficult. Most of the millet, sorghum, and sunflower crops are grown in the drier parts of the state (Figure 3.5) and may have highly variable crop densities/cover due to environmental influences and management practices such as non- tillage.

(a)



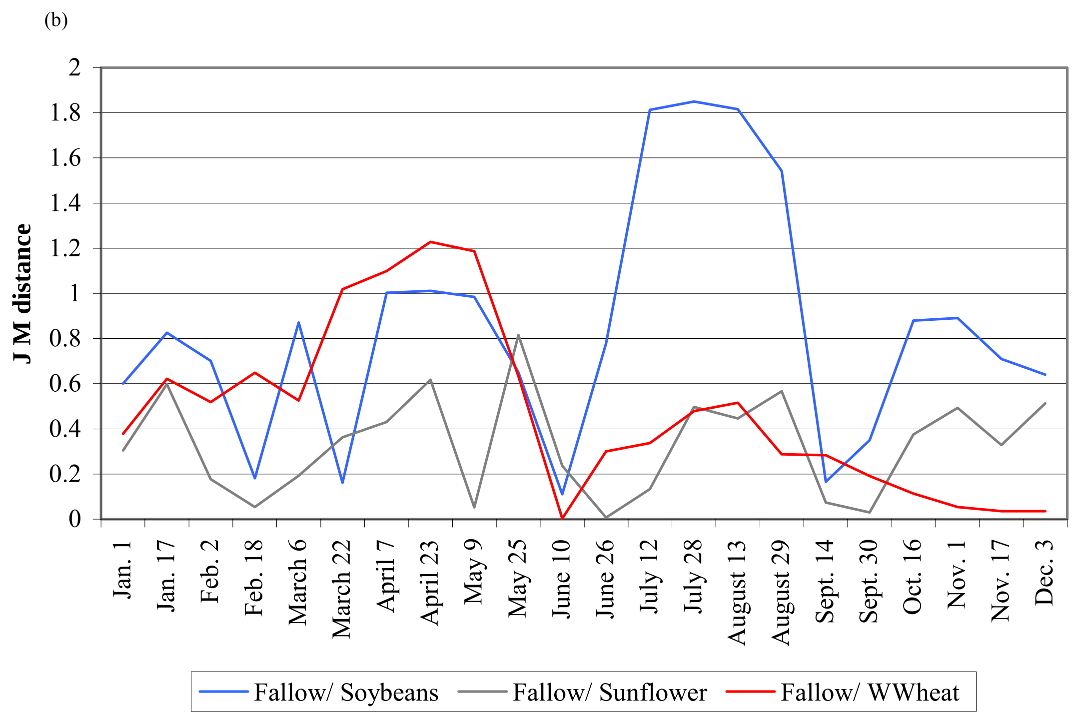


Figure 3.20 The JM distance values observed when comparing field site mean NDVI values for fallow and all seven crops.

A comparison of JM distances between common crop-pairs in Nebraska, as in Kansas (Wardlow et al., 2007) revealed that both alfalfa and winter wheat had high separability from other crops (maximum JM distances > 1.99) throughout much of the year in both states. The composite periods during which the separability was high are similar. In Nebraska however, alfalfa and winter wheat both had very high to perfect separability (maximum JM = 2) from summer crops between composite period of April 7 and May 25. In both states, the greatest separability among the summer crops occurred during the initial spring green up phase and/or the late senescence phase. The greatest separability among the summer crops in Nebraska was between corn and millet (JM = 1.8), while in Kansas it was between corn and soybeans

(JM = 1.61). In Kansas, fallow was highly distinguishable from other crops with JM distances >1.99; while in Nebraska, fallow and corn, and fallow and soybeans were the most separable (JM >1.8).

3.6 CONCLUSIONS

The aim of this study was to extend the work done in Kansas to Nebraska to further investigate the potential of MODIS NDVI 250-m data in agricultural-related land cover research in another area of the Great Plains of the U.S.A. The objective of the research was to evaluate the applicability of time-series MODIS 250-m NDVI data for crop type spectral profile characterization and discrimination in Nebraska. Several major conclusions were drawn from this research.

First, each crop type had a distinctive MODIS 250-m NDVI profile corresponding to the crop calendar. Each crop's unique profile was as a result of differences in timing of green up, peak greenness, densities and structures of various crop's canopies, and senescence. Detailed scrutiny of cluster NDVI profiles of each crop type was able to highlight subtle variations at the crop level. Distinct spectral-temporal differences were discernible between NDVI profiles of alfalfa and winter wheat, and summer crops (corn, millet, sorghum, soybeans, and sunflowers). The timing of green up for alfalfa and winter wheat occurred in early spring (*i.e*. late March), much earlier than that of summer crops. The peak NDVI values (*i.e.,* peak greenness) were attained in mid-spring (*i.e.,* late April and early May) in contrast to summer crops whose peak NDVI values were attained in mid-summer (*i.e.,* early July and late August). Although summer crops displayed specific profiles corresponding to their documented crop calendars, corn, soybeans, and sorghum could be distinguished from one another, this was not easy for millet and sunflower.

Second, a visual (*i.e.,* using graphs) and numerical (*i.e.*, using statistical-based JM distance values) comparison of the average, state-level time-series NDVI profiles showed that the crop types were separable at different times of the growing season based on their phenology-driven spectral-temporal differences. Winter wheat and alfalfa, winter wheat and summer crops, and alfalfa and summer crops were clearly separable. Specific summer crops were not as easily distinguishable due to their similar crop calendars. However, their greatest separability, particularly between corn and the other four summer crops, occurred during the initial spring green up phase and/or senescence phase. Fallow was clearly separable from all crops during their respective growing seasons. However, there was relatively low separability with millet in early April and late-May and with sorghum in late July.

Third, it was found that the crop type spectral profile characterization and discrimination results obtained in Nebraska were in many aspects similar to those obtained in Kansas, thus confirming that the methodology used in the Kansas study would extend to other regions in the Great Plains of the U.S.A.

Finally, this research has further confirmed that MODIS NDVI 250-m data have great potential in agricultural related land cover research in the Great Plains of the U.S.A. The results have demonstrated that crop type spectral profile characterization and discrimination are invaluable steps before crop type classification and mapping efforts are accomplished.

In future research, (i) NDVI signatures for irrigated crops should be assessed since Nebraska has more crops under irrigation, (ii) regional, crop-specific NDVI signals should also be assessed to understand the spatial variability for each crop across an area as large as Nebraska, and (iii) a similar study including agricultural and natural cover types should be carried out in Zambia as a preliminary investigation into the applicability of MODIS data.

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Chapter 4

A COMPARATVE ANALYSIS OF PHENOLOGICAL CURVES FOR MAJOR CROPS IN KANSAS

CHAPTER SUMMARY

Mapping land use and land cover (LULC) patterns at various geographic scales on a regular basis provides information essential for strategic planning in agro-ecosystems. Reference data sets are vital in remote sensing-based research activities because they are used for (i) calibration and validation of remote sensing imagery and its data products, (ii) feasibility studies for airborne/spaceborne missions and (iii) basic investigation of the relationship between physical or biochemical properties and the electro-magnetic reflectance of objects (Hüni *et al*., 2007). However, reference data sets are often difficult and/or expensive to collect and therefore may not be available on an annual basis, even though it is often desirable to map land cover (especially crops) yearly.

The goal of this research was to conduct an initial investigation into whether time-series NDVI reference curve library for crops over a growing season for one year could be used to map crops for a different year. In this case, time-series NDVI library of curves for 2001 and 2005 were investigated to ascertain whether or not the 2001 data set could be used to map crops for 2005.

The 2005 16-day composite MODIS 250-m NDVI data and 2005 Kansas Common Land Unit (CLU) data layer from the USDA FSA were available for use. A *k*-means cluster

analysis of NDVI values from 1,615 field sites representing alfalfa, corn, sorghum, soybeans, and winter wheat was performed to identify validation sites with time-series NDVI spectral profiles characteristic of the major crop types grown in Kansas. After completing the field site refinement process, there were 1,254 field sites retained for further analysis, referred to as 'final' field sites. The methodology employed to evaluate whether or not the MODIS-based NDVI profiles for major crops in Kansas are stable from year-to-year, involved both graphical and statistical analyses. First, the time-series NDVI values for 2005 from the final field sites were aggregated by crop type and the crop NDVI profiles were then visually assessed and compared to the profiles of 2001 to ascertain if each crop's unique phenological pattern was consistent between the two years. Second, separability within each crop class in the time-series NDVI data between 2001 and 2005 was investigated numerically using the Jeffries-Matusita (JM) distance statistic.

The results indicate that there was near-complete agreement between the winter wheat crop profiles, but there were some minor differences in the crop profiles for alfalfa and summer crops between the study years. The differences observed between the alfalfa profiles are mainly due to differences in 'growth and cut' cycles that were not in synchrony. However, the profiles of summer crops – corn, sorghum, and soybeans – displayed a shift to the right by at least 1 composite date, due to the heavy rainfall throughout the state in the month of June that limited the growth of corn and slowed soybeans planting, and late sorghum planting and emergence. The results, particularly for alfalfa and summer crops, seem to suggest that time series NDVI response curves for crops over a growing period for one year of valid ground reference data may not be used to map crops for a different year without taking into account the climatic and/or environmental conditions of each year.

4.1 INTRODUCTION

Mapping land use and land cover (LULC) patterns at regional, state, and global scales on a repetitive basis has been recognized (Turner, *et al*., 1995; NRC, 2001; NASA, 2002) as a way of providing 'up-to-date' LULC information and characterizing major human-environmental interactions. Crop mapping on an annual basis, therefore, can provide improved estimates of near real time changes in crop production and can greatly benefit strategic planning in agro-ecosystems.

Remote sensing techniques have been extensively used in crop mapping during the past several decades (Congalton *et al*., 1998; Ehrlich *et al*., 1994; Maxwell and Hoffer, 1996; Oetter *et al*., 2001; Xiao *et al*., 2006), providing timely assessments of conditions, changes in growth, and development of agricultural crops. In all these mapping efforts, the availability of high quality ground reference data sets has been crucial. Hüni *et al*. (2007) and Lillesand *et al* (1998) pointed out that most reference data sets are collected for purposes of training computer algorithms to recognize various land cover categories latent in the satellite imagery and assessing the categorical accuracy of the resulting classification. Different ground reference data collection methods are employed, depending on the application, the availability of primary sources of reference data, and the adequacy of interpretation and field staff (e.g. Allen *et al.,* 2002; Khorram *et al*., 2001; Wardlow *et al*., 2007; Wickham *et al*., 2004). Although reference data are vital in remote sensing-based research projects, in many cases and for various reasons, the data are of poor quality. There are several issues that impact the availability of high quality reference data. First, the collection of reference data is an expensive process and adequate financial resources are often lacking to support this activity (Bronsveld *et al*., 1994). This problem is particularly common in the third world countries with inadequate resources at their disposal. Second, reference data sets, especially those related to plant phenomena that change over time, are often few in number and limited in their spatial and temporal validity (Bronsveld et al., 1994). Lillesand *et al*. (1998) acknowledged this constraint, by pointing out that ground reference data generally cannot be collected for large portions of an entire project area, or even for multiple time periods. Finally, in some instances the reference data are inadvertently inaccurate, outdated, unobtainable due to legal restrictions (e.g., inaccessibility to land parcels), or the locations are not easily accessible.

Although different reference data collection methods are available, most are time consuming, require substantial financial resources, and/or may not be undertaken on an annual basis. Dynamic agro-ecosystems, such as the ones found in the U.S. Great Plains create a demand for collecting crop-related reference information and crop-related mapping activities on a regular basis. This research therefore serves as an initial investigation into whether time-series NDVI reference curve library for crops over a growing season for one year can be used to map the same crops for a different year in the same location. In this case, time-series NDVI library of curves for 2001 and 2005 were investigated to ascertain whether or not the 2001 data set could be used to map crops for 2005. An extensive, valid ground reference data set is available for the state of Kansas, which was created for several MODIS-based crop mapping and monitoring projects conducted for 2001 (Wardlow and Egbert, 2008; Wardlow *et al*., 2007; Wardlow *et al*., 2006). Due to the rigorous process of selecting the field sites and curve refinement against field truth information, the 2001 Kansas profiles used in the series of these projects were considered to be a valid standard with which to compare. A 2005 Kansas Common Land Unit (CLU) data layer from the USDA Farm Service Agency (FSA) was available for use. The CLUs are polygons that correspond to individual field parcels for which the specific crop types grown are reported on annual basis by farmers and attributed to each polygon. Separate databases for five major crops (alfalfa, corn, sorghum, soybeans, and winter wheat) were created using GIS operations to select non-irrigated fields larger than 32.4 ha (80 acres, approximately five 250-m MODIS pixels) from the CLU data layer. The time-series NDVI values from 2005 MODIS were extracted using center points of the selected CLU polygons and refined using a *k*-means cluster analysis of NDVI values. The 2001 and 2005 sets of MODIS-based spectral profiles were subsequently compared visually as well as statistically using the Jeffries-Matusita (JM) distance statistic (Richard and Jia, 1999).

4.2 RESEARCH OBJECTIVE/QUESTION

This research was initiated out of the recognition that reference data sets are often difficult and/or expensive to collect and therefore may not be available on an annual basis, even though it is often desirable to map land cover (especially crops) yearly. Hence the following key research question regarding this work in Kansas was addressed: Are MODIS-based NDVI spectral profiles of major crops (alfalfa, corn, sorghum, soybeans, and winter wheat) different between 2001 and 2005? The assumption was that the MODIS-based NDVI profiles of major crops in Kansas would be stable from year-to-year with minor variations resulting from inter-annual climatic differences (both in precipitation and temperature). If this scenario were found to be true, it would be possible to use multi-temporal NDVI curve library for crops over a growing season for one year, created from high quality and complete reference data set, to map crops for a different year without any curve adjustments. To address the key research question, two sets of MODIS 250m NDVI spectral profiles from different years were visually compared and statistically evaluated using the Jeffries-Matusita (JM) distance statistic (Richards and Jia, 1999) to determine their level of similarity.

4.3 STUDY AREA

This study was conducted in the state of Kansas (Figure 4.1). Kansas covers an area of 21.3 million ha (82,282 square miles) of the U.S. Central Great Plains.

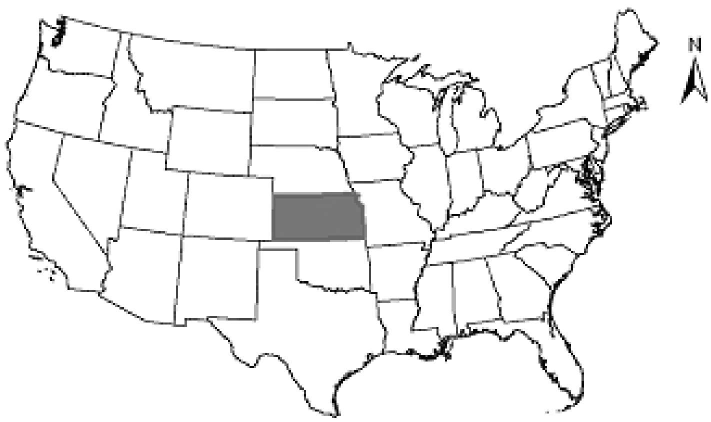


Figure 4.1 The state of Kansas study area map

The state has a mid-continental temperate climate with a pronounced east-west precipitation gradient. This gradient strongly influences the vegetation types, cropping patterns, and associated agricultural management practices. On average, western Kansas receives 460-510 millimeters (mm) of precipitation per year, central Kansas receives 900 mm, and eastern Kansas receives 890-1020 mm. Seasonal temperatures are highly variable with mean low temperatures of – 6^{o} C in January and mean high temperatures of 32^{o} C in July. The majority of the precipitation falls during the growing season from April through September.

Extensive grasslands dominate the Kansas natural vegetation landscape. In the west, sparse rainfall gives rise to short-grass prairie, while increased rainfall in the central part of the state generates mixed-grass prairie. In the east, adequate precipitation occurs to support tall-grass prairie that intermingles with oak-hickory deciduous forest in the far eastern part of the state. Its has been observed that most of the remaining grasslands in the western two-thirds of the state are native, having never been plowed, and are primarily used for grazing domestic livestock, while in the tall-grass prairie region, grazing is also prevalent, but many grasslands (both introduced and native) are managed for hay production (Egbert *et al*., 1998).

A larger portion of the state's total area is intensively cropped with alfalfa (*Medicago sativa*), corn (*Zea mays*), sorghum (*Sorghum bicolor*), soybeans (*Glycine max*), and winter wheat (*Triticum aestivum*). Eastern Kansas generally receives adequate precipitation to support mainly corn and soybeans production without irrigation, and fallow is non-existent. In semi-arid western Kansa, alfalfa, corn, and soybeans are grown under irrigation because of limited precipitation. High crop production levels are maintained due to extensive irrigation from primarily groundwater sources and dryland farming techniques (e.g., crop-fallow rotations and non-till farming). The non-irrigated areas of western Kansas are planted to dryland crops such as sorghum or winter wheat or remain fallow to conserve soil moisture for crop production the next year. The variability in the NDVI signals for a specific crop exhibited across the state is a confirmation of regional variations in climate and management practices (Wardlow *et al*., 2006). It has further been noted that Kansas also contains large acreages of former cropland that are now covered with native and non-native grasses as part of the USDA Conservation Reserve Program (CRP) (Egbert *et al.,* 1998).

4.4 DATA AND METHODS

A 12-month time-series of 16-day composite MODIS 250-m NDVI data for 2005 for field sites of five cover types – alfalfa, corn, sorghum, soybeans, and winter wheat - across Kansas was analyzed. A total of 1,254 field sites representing each of the five crop types under investigation were used as the basis for aggregating extracted time-series NDVI values and creating NDVI phenological curves. The 2001 curves were then compared to those from 2005. A brief discussion of the data and methods used is provided below.

4.4.1 Time-Series MODIS VI Data

In recent years, the application of MODIS data has become widespread among LULC research scientists. More literature is becoming available on crop condition and yield prediction (Doraiswamy *et al*., 2004; Muratova *et al*., 2005; Reeves *et al*., 2005; Xu *et al*., 2005) and crop classification and mapping (Doraiswamy *et al*., 2003; Wardlow and Egbert, 2008; Xiao *et al*., 2006; Xavier *et al*., 2006). The MODIS Land Science Team provides a suite of standard MODIS data products to users, which include the 16-day NDVI and enhanced vegetation index (EVI) composites. The MODIS NDVI serves as a 'continuity index' to the existing AVHRR NDVI record (Lindsey & Herring, 2002). The procedure for generating composited, MODIS VI products is the 'constrained view angle' maximum value compositing (CV-MVC) method, in which the highest NDVI value from a series of multitemporal georeferenced images within a specified range of view angles from nadir is retained for each pixel location in order to minimize cloud and atmosphere contamination and standardize sun/view angles (Huete *et al.,* 2002 & 1999; van Leeuwen *et al.,* 1999). MODIS is an improved instrument due to its better design (e.g., solar diffuser, solar diffuser stability monitor, spectro-radiometric assembly, and high level of geolocational accuracy) (Guenther *et al.,* 2002; Wolfe *et al.,* 2002). MODIS offers a unique and improved combination of spectral (36 bands), temporal (daily global coverage), spatial (0.25 to 1 km), and radiometric (12-bits) attributes, compared to previous sensors (Lindsey & Herring, 2002). Other desirable attributes include cost-free status and rapid availability of various products

The 16-day composite MODIS 250-m NDVI data (MOD13Q1 Version 004) spanning from January 1 to December 19, 2005 were acquired from the NASA Earth

Observation System Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/). The MODIS dataset comprised 874 tiles (38 per composite period) for North America. For each composite period, the MODIS NDVI data were extracted for each tile and the data were mosaicked and reprojected from the Sinusoidal to the Albers Conical Equal Area projection. The reprojected mosaics, 23 in total, were then sequentially stacked by composite period and subset to the Kansas state's boundary to produce the final time series data sets of Kansas.

4.4.2 Common Land Unit (CLU) and Field Site Database for 2005

The USDA FSA has long been involved in the acquisition, use, and distribution of large print aerial photography (photomaps) to achieve their farm program management tasks (Gabbott, 2003). The main purpose of the aerial photography enlargements was to provide an accurate geospatial record of farm tracts and field boundaries (Gabbott, 2003; Williams, 2004). The tract and farm field boundaries, known as Common Land Units (CLUs) were delineated on the aerial photography enlargements by FSA staff as a means to provide a visual representation of farm fields, thus allowing a common, intuitive way for staff and farmers to interact and record planted acreages (Williams, 2004). The USDA-FSA defines a CLU as an individual contiguous farming parcel, which is the smallest unit of land that has a permanent contiguous boundary; common land cover and management; common owner and/or a common producer association (USDA-FSA, 2001; 2007).

According to Gabbott (2003), millions of aerial photography enlargements have been produced since the 1930's and many of them are still in use. Over the past years however, the photo enlargements have changed as a result of the source imagery. Source imagery was flown at various scales including 1:20,000 during the period of 1938 – 1979, high altitude scales of 1:60,000 and 1:80,000 during the period of 1980 – 1987, and 1:40,000 scale during the period of 1987 to present. When FSA began implementing GIS in 1999 to better manage farm records and geospatial data and to enhance program delivery, the National Digital Orthophoto Program (NDOP) imagery were used to delineate CLU boundaries with aerial photographic enlargements as a reference. As a result of the need to meet FSA's evolving requirements for imagery, the National Agricultural Program (NAIP) was established in 2003. The NAIP provides FSA with 9" by 9" large format color digital imagery at 1:40,000 scale for the annual compliance program every year, and also to provide USDA Service Center agencies with current replacement orthophotography base imagery on a 5-year cycle (Williams, 2004). The NAIP imagery is used to maintain CLU data continuously in the USDA county-based Field Service Centers.

The USDA-FSA has outlined some of the many uses for CLUs (FSA 2001; 2007). Although the potential uses for CLUs are many, most work is focused on replacing current paper maps with digital images, and using GIS to achieve greater accuracy in acreage calculations (FSA, 2001; 2007). CLUs are also used to generate agricultural training and validation data used in producing the USDA NASS Cropland Data Layer (CDL) (Allen *et al.*, 2002). Since CLUs have the potential of providing up-to-date farm records, it is therefore a valuable resource for generating ground reference data sets for remote sensing-based applications.

A 2005 Kansas CLU data layer was available from the USDA FSA. However, only 64 counties had the necessary attributed data. Due to limited time, only non-irrigated fields were considered for this study. Separate databases for the five major crops were created by selecting non-irrigated fields larger than 32.4 ha (80 acres approximately five 250-m MODIS pixels) from the CLU data layer using GIS operations. Point-labeling all CLUs created center points for each crop polygons. The total number of initial samples for 2005 was 1,615 (Table 4.1) and the final sample size was 1, 254 (Table 4.1), after the initial reference data set was subjected to cluster analysis (Romesburg, 2004), using *K-means* clustering, as explained in the methods section below.

Table 4.1: Kansas non-irrigated crop types and sample size for 2001 and 2005

Crop Type	2001 sites after refinement	2005 sites before refinement	2005 sites after refinement
Alfalfa	119	149	138
Corn	279	348	290
Grain Sorghum	319	398	268
Soybeans	219	274	230
Winter Wheat	356	445	327
Total	1,292	1,615	1,254

4.4.3 Kansas Average NDVI Profiles for 2001

A total of 2,800 (i.e. non-irrigated = 1,292; irrigated = 1,508) verified field sites in Kansas were used by Wardlow *et al*. (2007) to extract time-series NDVI values from 2001 MODIS data. Average NDVI profiles were created for the five major crops of alfalfa, corn, sorghum, soybeans, and winter wheat. To refine the curves of these crop types, the profiles were visually evaluated to verify that their spectral characteristics were consistent with the phenology of the crop type reported by the FSA. Each refined curve was considered a standard NDVI profile for the respective crop type in Kansas. Due to the rigorous process of selecting the field sites and curve refinement against field truth, the 2001 Kansas profiles were considered to be a valid standard with which to compare the 2005 profiles. Although slight curve time-shifts were anticipated between 2001 and 2005 because of variation in precipitation management practices, and regional shifts in a crop's NDVI curve that were found across Kansas in 2001 (Wardlow *et al*., 2007) it was expected that the curve patterns would be the same.

4.4.4 Methods

A total of 1,615 initial field sites for 2005 (Table 4.1) representing the five crop types under investigation were used as a basis for extracting time-series NDVI values. The extracted NDVI data from the initial field sites for each crop type were subjected to Cluster Analysis (Romesburg, 2004), using *k-means* clustering, as a way of evaluating variability among field sites within each crop type, and to identify and eliminate outliers. Several cluster sizes were tried and in each case profiles were plotted and visually examined. Since some larger cluster sizes did not have members, the maximum cluster size of 10 was assumed adequate and subsequently 10 clusters were retained for each crop. The 2005 NDVI cluster profiles were visually compared to the 2001 MODIS-based profiles for the same crops in Kansas. Each crop's NDVI cluster profiles that were consistent with the spectral-temporal profiles of the same crop in Kansas were aggregated to represent crop-specific state-level multi-temporal NDVI profiles. Outliers and sites atypical of Kansas's crop phenology (361 in total) were identified and removed. The final field sites, totaling 1,254 (Table 4.1) whose average NDVI profiles appeared to be consistent with the known crop profiles, constituted the crop reference data set for Kansas in 2005. The 2005 sites, like for 2001, were appropriately distributed across the state (Figure 4.2) thus were considered to be a good representation of the crop distribution pattern in 2005.

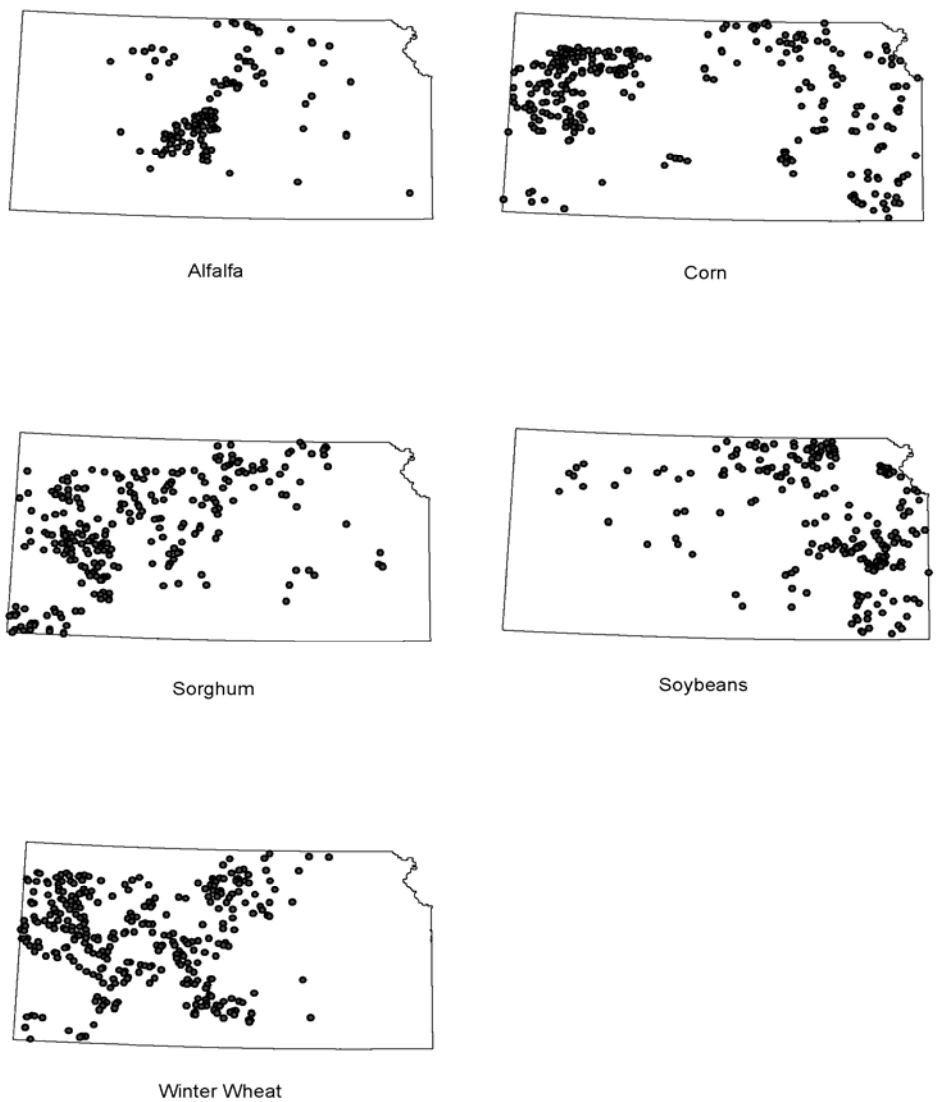


Figure 4.2 Retained field site locations by crop type for 2005 data set.

The methodology employed in this study to evaluate whether the MODIS-based NDVI profiles for major crops in Kansas are stable from year-to-year, involved both graphical and statistical analyses. First, the time-series NDVI values for 2005 the final field sites were aggregated by crop type and the crop NDVI profiles were then visually assessed and compared to the profiles of 2001 to ascertain if each crop's phenological pattern represented in NDVI response curves was consistent between the two years. Second, separability within each crop class in the time-series NDVI data between the two study years was investigated numerically using the Jeffries-Matusita (JM) distance statistic (Richards & Jia, 1999). JM distance has been affirmed in previous research work to be an effective measure for class separability (van Niel *et al.*, 2005; Wardlow *et al.*, 2007). Under normality assumptions, the JM distance between classes *i* and *j* is given by

$$JM_{ij} = 2(1 - e^{-a})$$

where $$a = \tfrac{1}{8}(\mu_i - \mu_j)^T \left(\frac{\Sigma_i + \Sigma_j}{2} \right)^{-1} (\mu_i - \mu_j) + \tfrac{1}{2} \ln \left(\frac{\left| \frac{\Sigma_i + \Sigma_j}{2} \right|}{\left| \Sigma_i \right|^{1/2} \left| \Sigma_j \right|^{1/2}} \right)$$

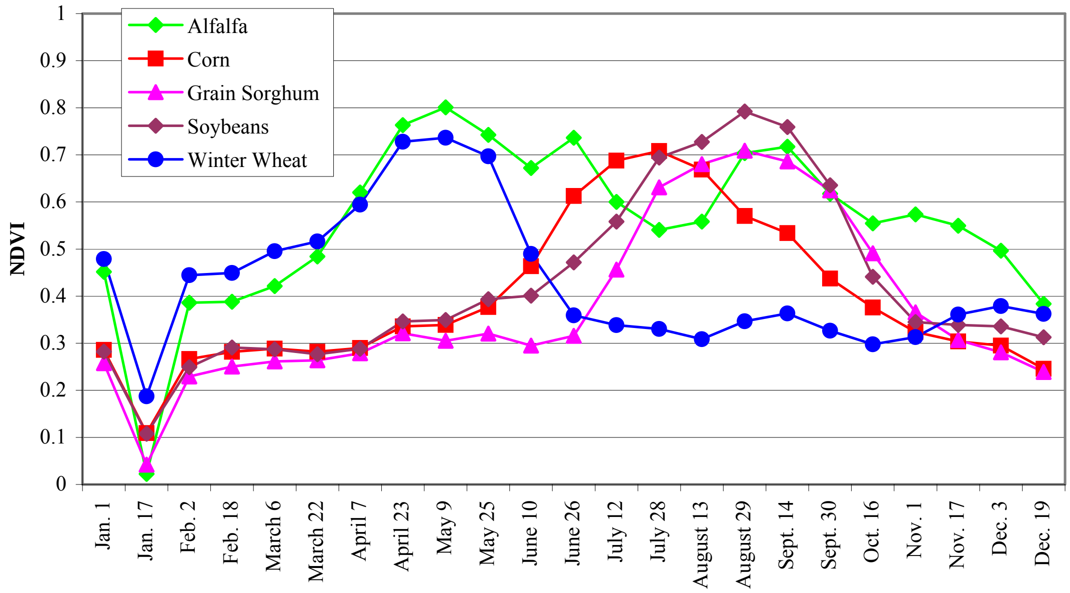
In this study, μ_i and μ_j are the class-specific mean NDVI values at a particular time period (or, more generally, vectors of mean values for a span of time periods), and $\sum_i$ and $\sum_j$ are unbiased estimates for the class-specific variance at the time period (or, more generally, covariance matrices for a span of time periods). JM distance values range between 0 and 2. A maximum JM distance of 2 between two classes means that the class-specific distributions are perfectly distinguishable from each other, while a minimum JM distance of 0 indicates that two class-specific distributions are indistinguishable.

4.5 RESULTS and DISCUSSION

4.5.1 Time-Series NDVI Profiles and Crop Phenological Characteristics

The multi-temporal NDVI profiles for each crop type presented in Figure 4.2 (a) show that each crop type had a unique and well-defined profile in 2005, as a result of differences in the timing of green up, peak greenness, and senescence. Distinct spectral-temporal differences were discernible between NDVI profiles of summer crops (corn, sorghum, soybeans) and both alfalfa and winter wheat in the spring periods when summer crops were yet to be planted. There was clear mid-summer separability between alfalfa and winter wheat as alfalfa continued to experience 'grow and cut' cycles while winter wheat maintained low NDVI values after harvest. The timing of green up for alfalfa and winter wheat occurred in early spring (i.e. late March), which was much earlier than that of summer crops (i.e., May and June). Peak NDVI values (i.e. peak greenness) for alfalfa and winter wheat were attained in mid-spring (i.e. May) compared to summer crops whose peak NDVI values were attained in mid-summer (i.e. late July and late August).

(a) 2005



(b) 2001

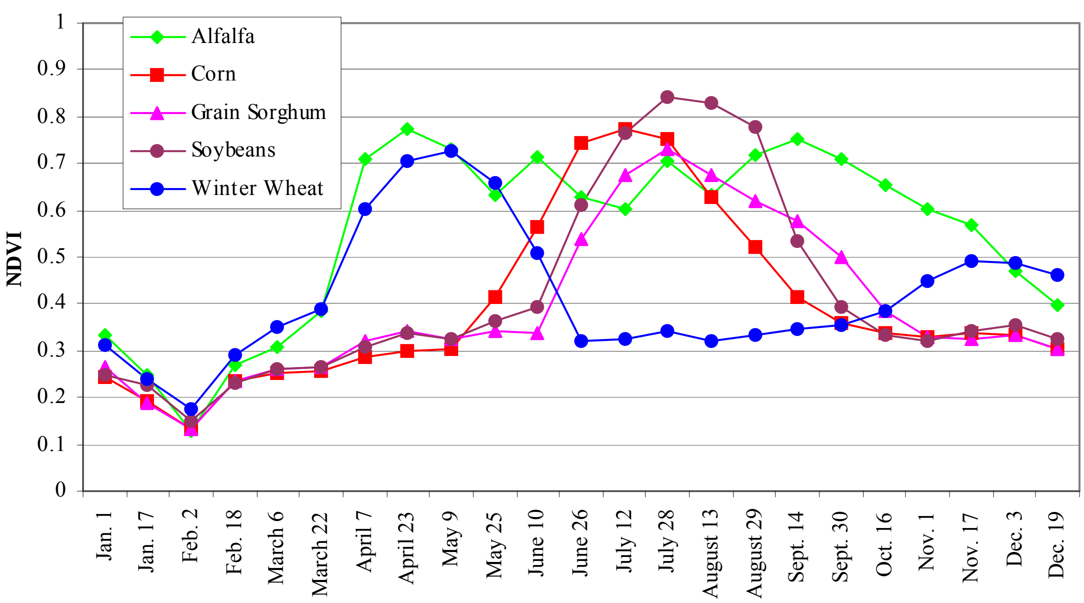


Figure 4.3 Time-series NDVI profiles (State average) for major crops in Kansas in (a) 2005 and (b) 2001.

In Kansas, summer crops are planted at relatively different times. Corn is typically the earliest planted summer crop (April to mid-May) followed by soybeans (mid-May to mid-June) and sorghum (late-May to late-June) (Shroyer *et al.*, 1996). The planting date differences among crops during both growing seasons (2005 and 2001) were clearly reflected in the phased timings of green up in Figure 4.3 (a) and (b). However, in 2005 the green up time lag among summer crops was relatively longer compared to 2001. There were also differences in the timing and value of the peak NDVI among summer crops, with soybeans having the highest NDVI values during both growing seasons. Typically, the soybeans canopy remains green until a very rapid drying occurs. The drying and leaf fall are more rapid than for corn and sorghum, which results in a more rapid NDVI decrease in late summer. The general crop spectral patterns observed for 2005 were similar to the 2001 NDVI profiles in Figure 4.2 (b). Figure 4.3 Time-series NDVI profiles (State average) for major crops in Kansas in (a) 2005 and (b) 2001.

4.5.2 Inter-Annual Comparison of Crop NDVI Profiles

In this section, the assessment of separability between specific crop types in the time-series NDVI data was done by visual comparison of 2005 and 2001 multi-temporal NDVI profiles, and numerically using the JM distance statistic. In both cases state averages were used.

Visual Comparison

A total of 5 graphs were visually evaluated to determine the extent of crop separability between the two reference years.

Alfalfa

In 2005, the crop's phenological characteristics and the 'growth and cut' cycles were visible in the time-series NDVI data, as illustrated by the profile of the state average in Figure 4.4. The typical alfalfa curve characterized by a steep ascending phase resulting from the rapid increase in NDVI values during the early spring observed in 2001, seems to be somewhat subdued in 2005. In 2005, the first peak NDVI value of 0.80 attained by May 9 was relatively higher compared to 0.77 attained by April 23. According to Shroyer *et al*., (1998), alfalfa is typically cut three or four times per year in Kansas with the first cutting in late-May or early June. For instance, cuttings in 2005 occurred during June 10, July 12, and October 16 composite periods, while in 2001 occurred in May 25, June 26, and August 13 composite periods. Although readily discernible, the 'growth and cut' cycles do not coincide because they took place at slightly different times of the growing season.

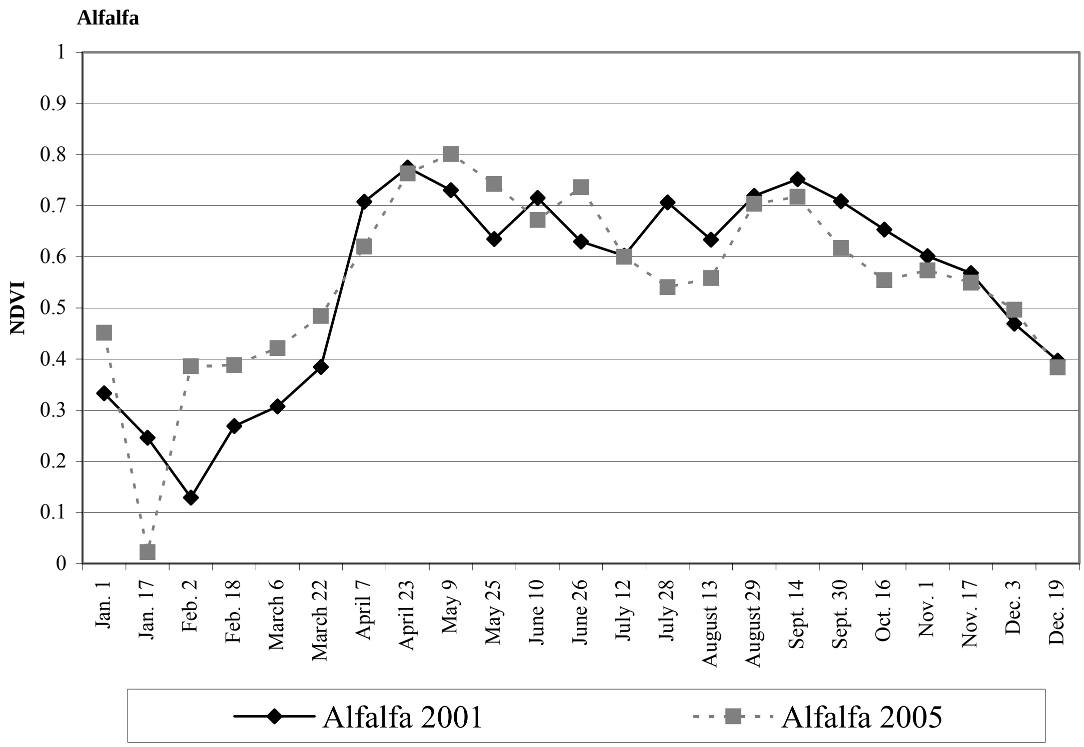


Figure 4.4 Time-series l NDVI profiles (state average) for alfalfa in Kansas.

Winter Wheat

Both the 2001 and 2005 state average winter wheat NDVI profile characteristics (Figure 4.5) reflect the distinctive crop calendar of the crop planted and emerging in the fall (usually in September or October) when soil moisture is optimum for germination and plant emergence, crop dormancy over the winter and breaking dormancy and reinitiating growth in the spring (March), followed by rapid growth and maturity in the spring (Paulsen *et al.*, 1997). In both years, winter wheat grew rapidly, with the 2005 profile displaying slightly higher NDVI values from the April 23 to May 25 composite periods. Although both profiles displayed a second smaller NDVI peak in November and December corresponding to the emergence and growth of the following year's crop, the 2001 peak was relatively higher.

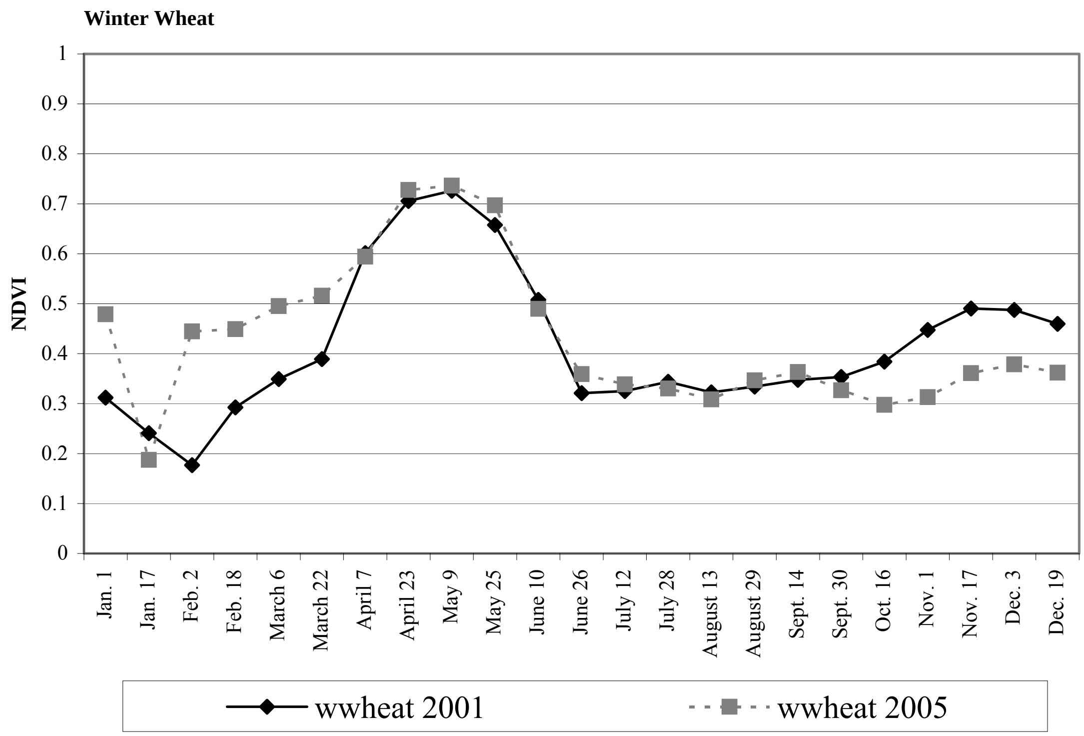


Figure 4.5 Time-series NDVI profiles (state average) for winter wheat in Kansas.

Corn

In Kansas, the planting of corn for grain usually occurs between early-April and late-May (Shroyer *et al.,* 1996). Seedling emergence usually occurs in six to ten days followed by a rapid development of vegetative material. When vegetative growth nears completion, the ear develops very rapidly followed by flowering and grain filling (McWilliams *et al.*, 1999). The crop growth usually requires about 130 to 150 days across the U.S. central Corn Belt

(Neild and Newman, 1990) and harvesting is carried out between late-September to early-November (UDSA, 1997).

Figure 4.3 shows that corn had the earliest green up between May 9 and May 25, among summer crops. However, the 2005 profile (Figure 4.6) had a relatively lower maximum peak NDVI value of 0.71 reached by July 28, in comparison to 2001 that had a slightly earlier green up and a peak value of 0.77 reached by July 12, and a later senescence with the NDVI beginning to gently decrease by the August 29 composite period.

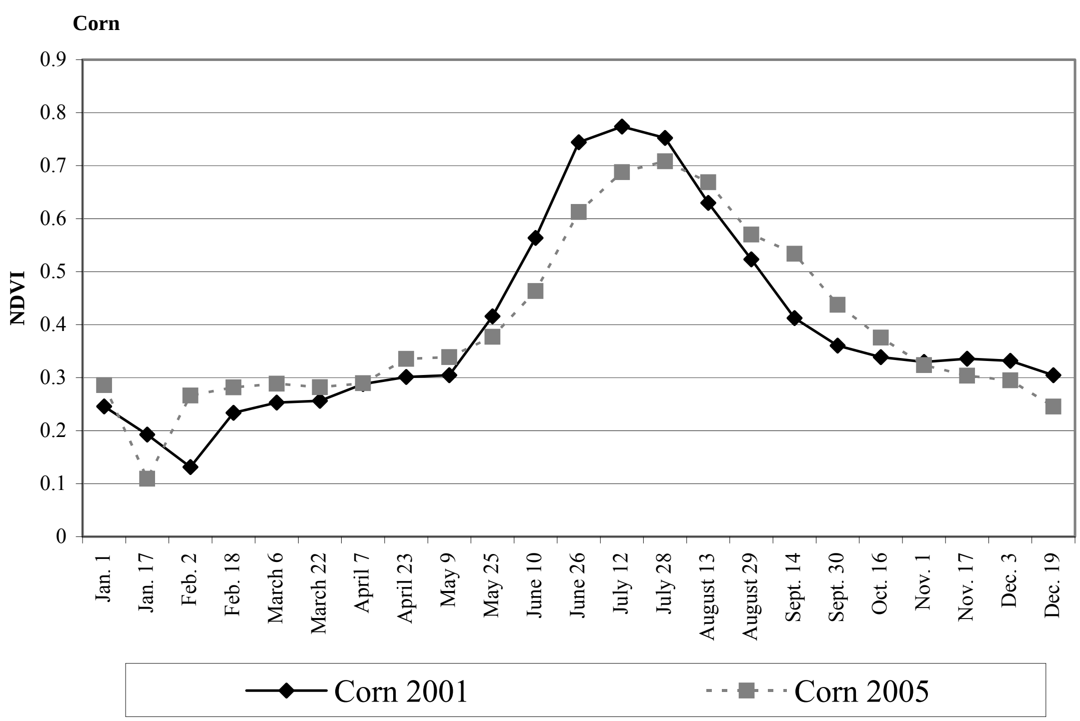


Figure 4.6 Time-series NDVI profiles (state average) for corn in Kansas.

The possible reason for the observed difference in the profiles between the two years is that in 2005, heavy showers were experienced throughout the state in the month of June. Hail damage and flooding were reported in some parts of the state, which reduced crop productivity and thus, slightly lower NDVI values (NASS, 2005a).

Sorghum

The sorghum profiles (Figure 4.7) show that the green up and peak NDVI occurred at different times between 2001 and 2005 growing seasons. In 2005, the green up occurred between the June 10 and June 26 composite periods, while in 2001 it was between the May 25 and June 10 composite periods. Sorghum peaked in 2005 during the August 29 period with a relatively lower NDVI (0.71) while in 2001 the peak was during the July 28 period with an NDVI value of 0.73. One of the reasons for the observed difference in the profiles is possibly due to sorghum planting that progressed behind normal (by a week) nearly all spring (NASS, 2006; NASS, 2005b). The other reason could be the difference of the date when more than 50% of the crop had emerged. In 2005, most of the crop had emerged by June 13 (NASS, 2005) in comparison to 2001, which was by June 6 (Wardlow *et al*., 2006). According to NASS (2006), the state of Kansas received only light showers throughout July and August. The dry weather gradually reduced crop condition so that by late-August only 37% of the crop remained in good to excellent condition. The above trend in weather maybe responsible for a relatively lower NDVI peak value in 2005.

Typically, the senescence behavior of sorghum exhibits a gradual decrease in NDVI, because the crop requires several weeks following physiological maturity to dry and reach harvest maturity (Vanderlip *et al.,* 1998). However, the 2005 sorghum profile exhibited a slightly different senescence behavior in comparison to the 2001 profile that exhibited a gradual NDVI decrease over a 2-month period (July 28 to September 30). The reason for the above observed contradictory senescence behavior is not known.

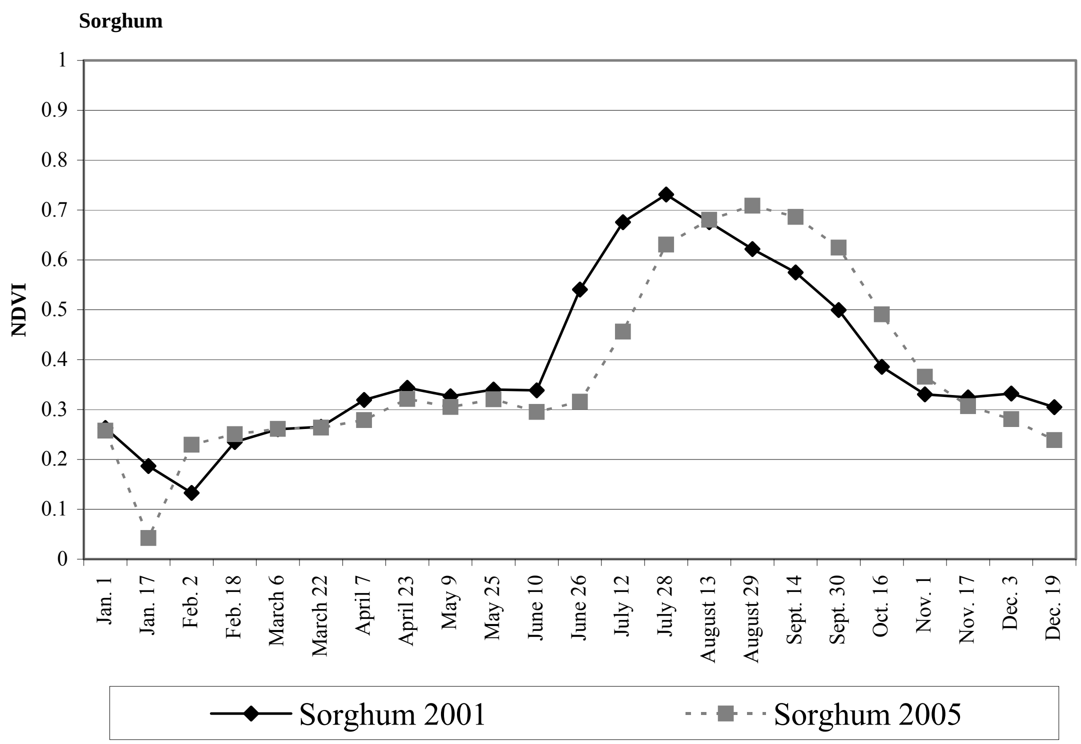


Figure 4.7 Time-series NDVI profiles (state average) for sorghum in Kansas.

Soybeans

Soybean planting takes place in mid-May to early-June and harvesting is from late-September to late-October (USDA, 1997). Emergence normally takes 5 to 10 days after planting, followed by rapid vegetative and reproductive phases (McWilliams *et al*., 2004). When the crop attains full maturity, the green foliage changes color as it dries up and rapid leaf drop occurs after desiccation (Rogers, 1997), and subsequently the crop is harvested beginning around September 19.

The soybean profiles (Figure 4.8) are consistent with the above crop calendar and indicate that the green up during 2001 and 2005 growing seasons occurred during the June 10 composite period, but that green up was much more rapid in 2001.

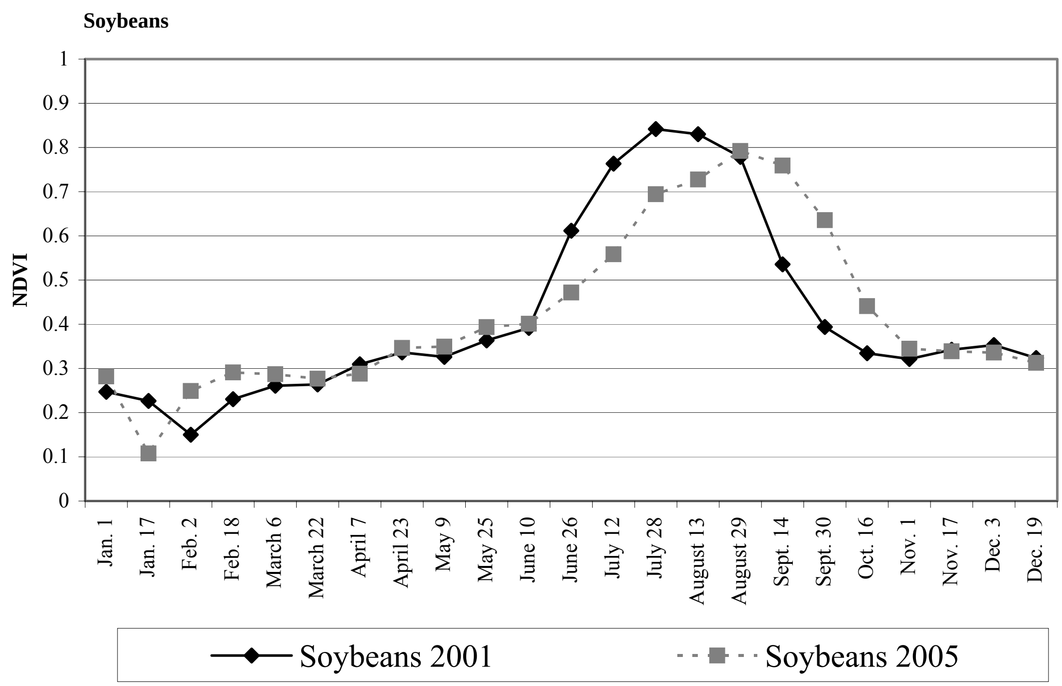


Figure 4.8 Time-series NDVI profiles (state average) for sorghum in Kansas.

In 2005 soybeans experienced slow growth after the composite period of June 10, possibly because of slowed soybeans planting resulting from locally heavy showers during the month of June (NASS, 2005b). According to NASS (2006), soybeans planting progress was slightly above the 5-year average for most of the spring. By mid-June, however, frequent rainfall throughout the state had slowed progress. In late-July, dry weather prevailed across the Plains with severe heat causing crop stress (NASS, 2005b). Soybeans peaked during the period of August 29 in 2005, one month later than 2001, had a relatively lower NDVI value (0.79), and a late senescence in comparison to 2001.

JM Distance Statistic

After the JM distance statistic was calculated for the 5 crop pairs, the pair-wise JM distances were plotted in graph form. Alfalfa and winter crops (Figure 4.9) were separated from the summer crops (Figure 4.10) to avoid clutter in one graph. None of the crop pair's comparison produced a perfect match (JM = 0) or showed the crops were completely different between the two years (JM=2). However, the JM distance values for all crops, although above 0, were very low (<0.3) throughout all the crops' growing seasons.

The JM distance values for alfalfa, a perennial crop, were generally lower than 0.4 during the whole crop growing period (Figure 4.9). There is a reduction in the JM distance value from 0.4 to 0.04 in March and April, which corresponds to the time period during which alfalfa breaks winter dormancy and begins photosynthetic activity/growth (Shroyer *et al*., 1998). The three noticeable spikes in the values by the composite periods of May 9 (JM=0.25), June 26 (JM=0.3), and July 28 (JM=0.2) are as a result of the unsynchronized alfalfa cuttings patterns between 2001 and 2005 that has been explained earlier in this section.

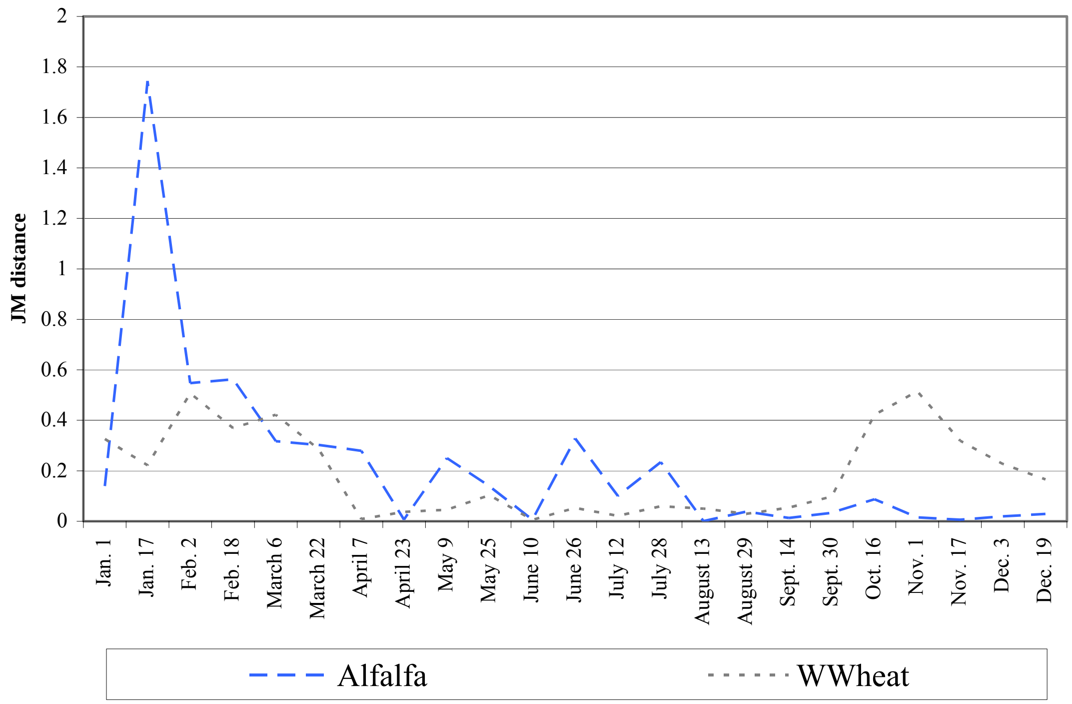


Figure 4.9 The JM distance values observed when comparing 2001 and 2005 field site mean NDVI values for alfalfa and winter wheat.

During the winter wheat growing season, the JM distance values were below 0.1 (Figure 4.9). These small values indicate that there was minimal winter wheat difference between NDVI observations from 2001 and 2005. The JM distance value decreased from 0.2 to 0.01 between late March and early April, the time period during which winter wheat breaks winter dormancy and resumes growth (Paulsen *et al.*, 1997). The values remained low for the rest of the season until the months of October to November, when the peak value of 0.5 was reached between the 2001 and 2005, as was revealed in Figure 4.5. This high value may be due to differences in emergence and growth of the following year's crops, or a larger number of fields being idled and not planted in winter wheat during the fall.

During the summer crops' growing season, the JM distance for corn was below 0.2, suggesting low difference in the NDVI responses for corn between 2001 and 2005 (Figure 4.10). However, during the composite periods of June and July, the values were closer to 0.2 because of variation in green up, rate of growth, and maximum peak NDVI values between the months of June and July, as was evidenced in Figure 4.6. Sorghum had JM distance values of above 0.2 during the periods from June to July and September to October (Figure 4.10). However, the maximum value of 0.7 was observed at the composite date of June 26, the time period which displayed differences in green up and crop growth rate (Figure 4.7). During the month of September, the values were around 0.3 mainly as a result of differences in senescence periods. Soybeans reached higher JM distance values during the composite periods in September, with the maximum value of approximately 7.0 reached by September 14 resulting from the delayed crop growth in and especially senescence in 2005.

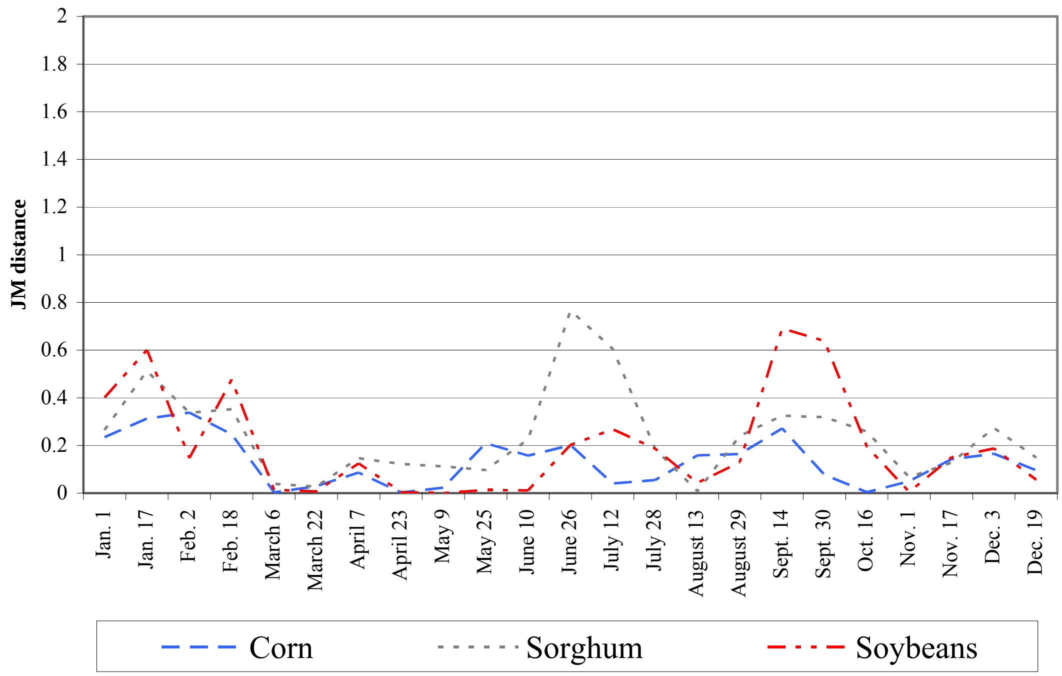


Figure 4.10 The JM distance values observed when comparing 2001 and 2005 field site mean NDVI values for corn, sorghum, and soybeans.

4.6 CONCLUSIONS

The goal of this research was to conduct an initial investigation into whether time-series NDVI response curves for crops over a growing season for one year might be used to map crops for a different year. In this case, time-series NDVI response curves for 2001 and 2005 were investigated to ascertain whether or not the 2001 data set could be used to map crops for 2005 or any other later years. The results indicate that there was near-complete agreement between the winter wheat crop profiles but there were some minor differences in the crop profiles for alfalfa and summer crops between 2001 and 2005. The differences observed between the alfalfa profiles were mainly due to differences in ‘growth and cut’ cycles that were not in synchrony. However, the profiles of summer crops – corn, grain sorghum, and soybeans – displayed a shift to the right by at least 1 composite date, indicative of the late crop emergence and a delayed growth and senescence cycle. In 2005, heavy showers experienced throughout the month of June while hail damage, and flooding reported in some parts of the state particularly affected the crop growth. The results, particularly for alfalfa and summer crops, seem to suggest that time series NDVI response curves for crops over a growing period for one year of valid ground reference data may not be useful for mapping crops for a different year without taking into account minor temporal shifts in the NDVI values due to inter-annual climate variations or changes in agricultural management practices. This study was limited in that only non-irrigated crops at state level were investigated and not more than two years were considered. In future research, the following should be considered:

(i) Investigate the NDVI responses for irrigated crops between 2001 and 2005. This is because the same irrigated crop may display differences in NDVI response between two time periods because of irrigation practices dictated by inter-annual climatic variation.

(ii) Explore the major crops' NDVI responses at the within-state regional level. In a series of studies by Wardlow *et al.* (2007 and 2006), it was shown that regional variations in climate and management practices had an influence on the considerable intra-class variability exhibited in the time-series MODIS data for a given crop. Therefore, the investigation of regional agreement between a crop's NDVI responses over multiple years might yield improved results.

(iii) Mapping of major crops using 2001 training data and 2005 MODIS NDVI data as a base. The focus would be to investigate how well the 2001 data does to map

2005 crops, by comparing the spatial accuracies of the two maps. The comparison of the 2005 map crop acreages with the USDA NASS crop statistics would also be undertaken.

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Chapter 5

SUMMARY

5.1 DISSERTATION OVERVIEW

5.1.1 Research Goal and Objectives

The goal of this study was to further investigate the potential of MODIS NDVI 250-m data for crop spectral characterization, discrimination, and mapping in the Great Plains of the USA using various exploratory approaches. This study had three general objectives, as outlined below.

First, explore ways of creating and refining a reference data set for remote sensing applications, when a suitable reference data set is unobtainable because it is expensive to collect, inadequate in spatial and temporal coverage, inadvertently inaccurate, outdated, legally restricted, or non-existent. The specific objectives of this research were to (i) produce a crop reference data set for Nebraska from the 2006 U.S. Department of Agricultural (USDA) Crop Data Layer (CDL), and (ii) refine the crop reference data set using *k-means* clustering (Romesburg, 2004) and visual assessment of each crop's normalized difference vegetation index (NDVI) cluster profiles.

Second, extend work previously done in Kansas by Wardlow *et al*. (2007) to Nebraska, several exploratory approaches were used to further investigate the potential of MODIS NDVI 250-m data in agricultural-related land cover research other parts of the Great Plains. The objective of this part of the research was to evaluate the applicability of time-series MODIS 250-m NDVI data for crop-type discrimination by spectrally characterizing and discriminating major crop types in

Nebraska using the reference data set collected and refined under research performed for the first objective. Two specific research questions were addressed: (i) do the spectral-temporal profiles of target crops derived from MODIS 250-m NDVI data correspond to their documented crop calendars? (ii) do these spectral-temporal profiles have adequate separablility for crop type identification and subsequently mapping?

Third, conduct an initial investigation into whether time-series NDVI response curves for crops over a growing season for one year could be used to classify crops for a different year. The following key research question regarding this work in Kansas was addressed: Are MODIS-based NDVI spectral profiles of major crops (i.e. alfalfa, corn, grain sorghum, soybeans, and winter wheat) different between 2001 and 2005? The assumption was that the MODIS-based NDVI profiles of major crops in Kansas would be relatively stable from year-to-year with minor variations resulting from differences in precipitation and temperature. If this scenario were found to be true, it would be possible to use NDVI response curves for crops over a growing season from one year, created from high quality and complete reference data set, to map crops for a different year without any curve adjustments. In this case, time-series NDVI response curves for 2001 and 2005 were investigated to ascertain whether or not the 2001 data set could be used to map crops for 2005. These two sets of MODIS 250m NDVI spectral profiles were visually compared and statistically evaluated using the Jeffries-Matusita (JM) distance statistic (Richards & Jia, 1999) to determine their similarity or separability.

5.1.2 Major Findings and Conclusions

In research component 1 (chapter 2), ways for reference data generation using GIS operations and reference data refinement using both *k-means* clustering (Romesburg, 2004) and visual assessment of each crop's NDVI cluster profiles were investigated as essential steps for developing a crop reference data set for Nebraska. The research demonstrated that it is possible to devise an alternative reference data set and refinement plan that addresses the unexpected loss or lack of training and validation data. The major conclusions from this work were that:

(i) CDLs and MODIS 250-m data were suitable for extracting field sites when adequate reference data are not available. The extraction technique was dependent on the existence of the two data sets and applying various GIS operations (e.g., raster layer separation using raster calculator, raster to polygon conversion, add x, y fields, and calculating values for each field) to create polygons from a CDL layer and computing centroids for each polygon.

(ii) *K-means* clustering (Romesburg, 2004) and visual assessment of crop-specific time-series NDVI data were appropriate techniques for refining a reference data set. However, the refinement process was time consuming because some centroids that fell just outside or inside the polygon boundaries had to be manually shifted to the middle of the polygon to ensure that the NDVI values extracted at the centroid locations were away from the polygon edges which would result in the use of NDVI values from mixed pixel cover types. The problem of centroids falling outside the polygon was encountered in circumstances were the contiguous polygon had an irregular shape, thus the center was located just outside, as illustrated in Figure 5.1.

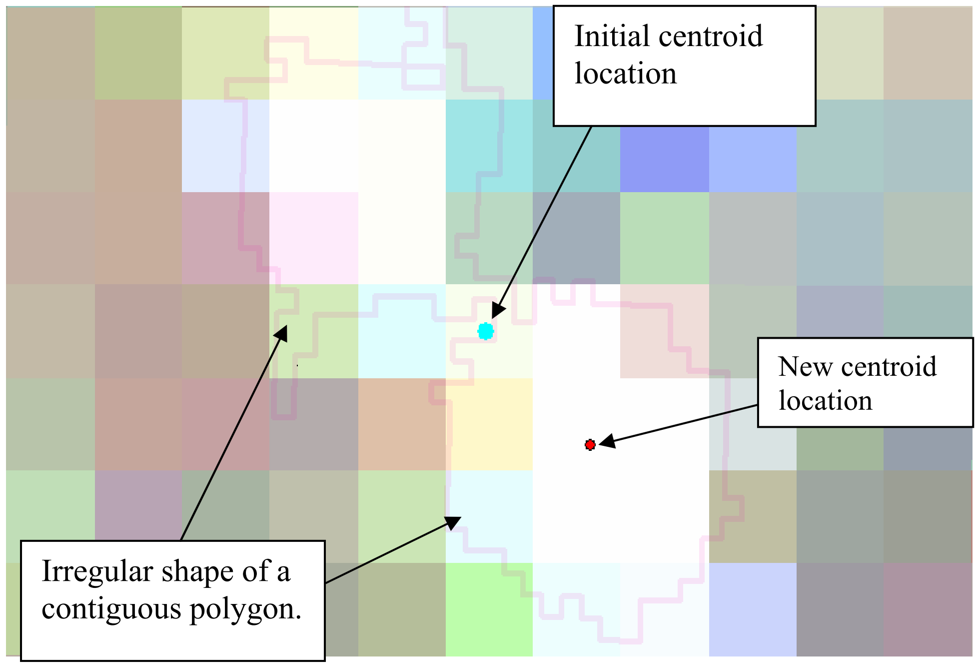

Figure 5.1 An illustration of a centroid falling just outside the irregular contiguous polygon.

In research component 2 (chapter 3) conducted in Nebraska, a combination of graphical and statistical analyses was performed to evaluate the applicability of time-series MODIS 250-m NDVI data for crop type discrimination in Nebraska. Class separability between specific crop types in the time-series MODIS 250-m NDVI was investigated graphically using time-series mean NDVI values along with the periodic-specific ±1 standard deviation of crop-specific NDVI values, and numerically using the Jeffries-Matusita (JM) distance statistic (Richard and Jia, 1999). The major conclusions from this work were that:

(i) Each crop type had a distinctive MODIS 250-m NDVI profile corresponding to the crop calendar of each respective crop (USDA, 1997). Each crop's unique profile was a result of different timings of green up, peak greenness, and senescence; as well as the crop's plant density and structure. Detailed scrutiny of cluster NDVI profiles of each crop type made it possible to highlight subtle variations at the crop level. For example, as expected, distinct spectral-temporal differences were discernible between NDVI profiles of alfalfa and winter wheat and the various summer crops (corn, millet, sorghum, soybeans, and sunflowers). The timing of green up for alfalfa and winter wheat occurred in early spring (*i.e.* late March), which was much earlier than for the summer crops. Peak NDVI values (*i.e.,* peak greenness) were attained in mid-spring (*i.e.,* late April and early May) in contrast to summer crops whose peak NDVI values were attained in mid-summer (*i.e.,* early July and late August). Although summer crops displayed specific profiles corresponding to their documented crop calendars, corn, soybeans, and sorghum could be distinguished from one another, this was not easy for millet and sunflower.

(ii) A visual (*i.e.,* using graphs) and numerical (*i.e.,* using statistical-based JM distance values) comparison of the average, state-level time-series NDVI profiles showed that the crop types were separable at different times of the growing season based on their phenology-driven spectral-temporal differences. Winter wheat and alfalfa, winter wheat and summer crops, and alfalfa and summer crops were clearly separable. Specific summer crops were not as easily distinguishable due to their similar crop calendars. However, their greatest separability, particularly between corn and the other four summer crops, occurred during the initial spring green up phase and/or senescence phase because corn is planted early, peak growth, maturity and harvest occur before sorghum and soybeans. Fallow was clearly separable from all crops during their respective growing seasons. However, there was relatively low separability with millet in early-April and late-May and with sorghum in late-July.

(iii) It was found that the crop type spectral profile characterization and discrimination results obtained in Nebraska were in many aspects similar to those obtained in Kansas (Wardlow *et al.*, 2007), thus confirming that the methodology used in the Kansas study would extend to other regions in the Great Plains of the U.S.A.

In research component 3 (chapter 4) conducted in Kansas, two sets of MODIS 250-m NDVI spectral profiles for 2001 and 2005 were visually compared and statistically evaluated using the Jeffries-Matusita (JM) distance statistic (Richards & Jia, 1999) to determine their similarity or separability. The major conclusions from this work are that:

(i) There was near-complete agreement between the winter wheat crop profiles, but there were some minor differences in the crop profiles for alfalfa and a difference of at least 1 composite period for all summer crops between 2001 and 2005. The differences observed between the alfalfa profiles are mainly due to differences in 'growth and cut' cycles that were not in synchrony. The profiles of summer crops – corn, grain sorghum, and soybeans – displayed a shift to the right by at least 1 composite date, indicative of probable late crop planting and emergence.

(ii) The offset curves for alfalfa and summer crops between 2001 and 2005 seem to suggest that time-series NDVI response curves for these crops over a growing period for one year of valid ground reference data may not be useful for mapping the same crops for a different year without taking into account minor temporal shifts in the NDVI values due to inter-annual climate variations or changes in agricultural management practices.

5.2 FUTURE RESEARCH DIRECTIONS

In future research involving reference data set creation, the following should be considered:

(i) Attempts should be made to automate the process of re-locating centroids that fall outside the polygons, and

(ii) Instead of visual profile comparison only, alternative mathematical techniques (e.g., curve fitting) should be explored to describe and compare each crop's known profile and the MODIS-based NDVI profile forms.

Further work should be done on the following:

(i) NDVI signatures for irrigated crops should be assessed since Nebraska has more crops under irrigation.

(ii) Regional, crop-specific NDVI signals should also be assessed to understand the spatial variability for each crop across an area as large as Nebraska. A regional analysis in Kansas by Wardlow *et al*. (2007) revealed that considerable intra-class variability existed in the time-series MODIS NDVI data for a given crop due to regional variations in climate and management practices.

(iii) A test should be done using 2001 training data to map 2005 MODIS time-series imagery (and perhaps vice versa) to validate whether the tentative conclusions reached in the component 3 research are correct.

This work would tell if the maps that were produced using the 2 years of training data were 'actually' different. If there was a systematic shift in all the crops' curves, then the relative differences would be maintained and similar classification results might be expected.

(iv) Similar studies including agricultural and natural cover types should be carried out in other parts of the world such as Zambia and the U.S., where ground reference data is often sparse, as a preliminary investigation into the extension of MODIS data for LULC characterization.

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